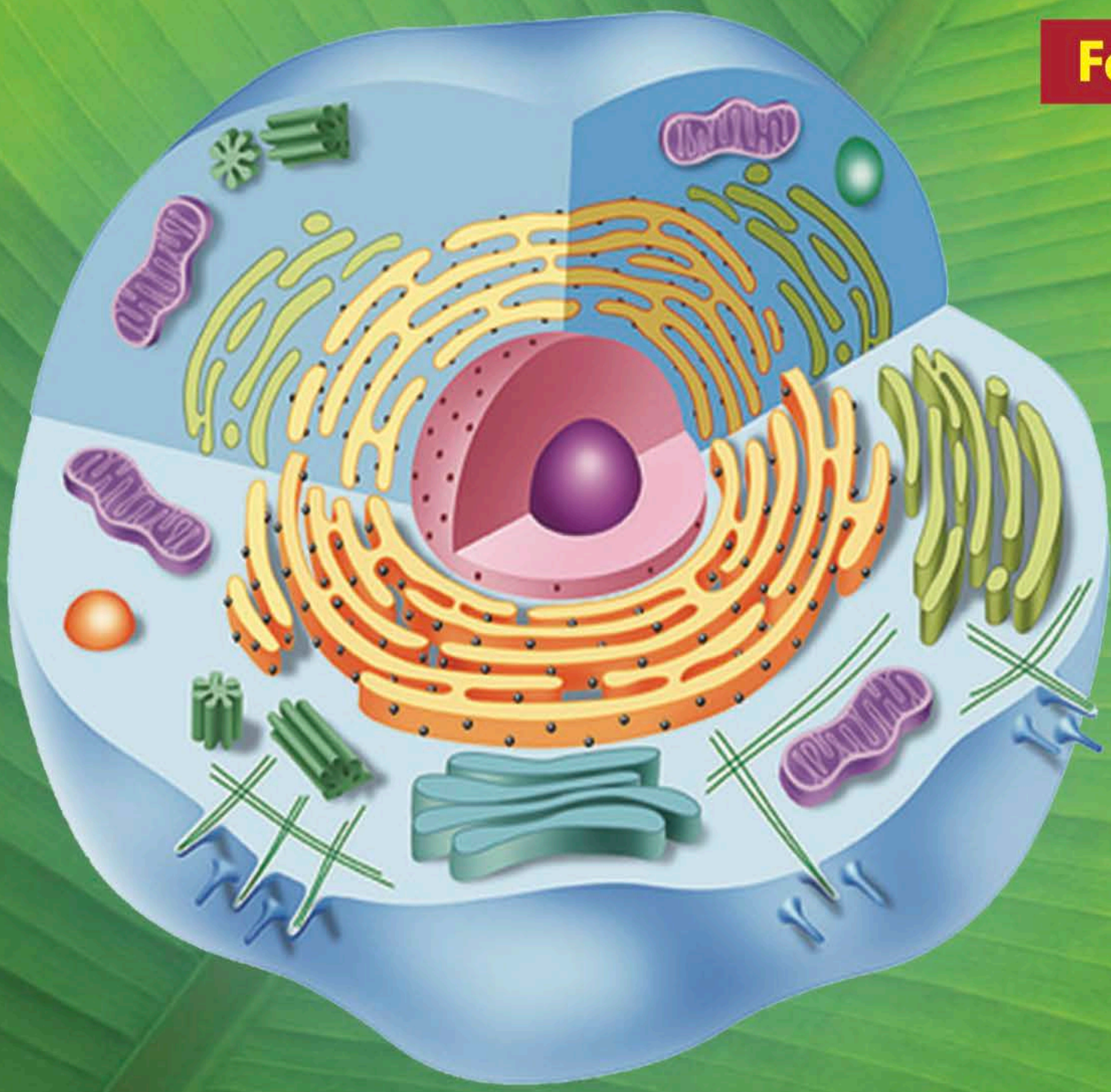
Biology

for Advanced Level Secondary Schools

Student's Book

Form Five



Tanzania Institute of Education

Biology

for Advanced Level Secondary Schools

Student's Book
Form Five

THE UNITED REPUBLIC OF TANZANIA
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Preface

This book *Biology for Advanced Level Secondary Schools*, is written specifically for Form Five Biology Students in the United Republic of Tanzania. The book is prepared according to the 2009 Biology Syllabus for Advanced Level Secondary Education Form V-VI, issued by the Ministry of Education and Vocational Training.

The Book consists of seven chapters, which are: Cytology, Principles of classification, Comparative studies of natural groups of organisms, Coordination, Nutrition, Gaseous exchange and respiration, and Regulation. In addition to the content, each chapter contains activities, illustrations, exercises and revision questions. Learners are encouraged to do all activities and answer all questions so as to enhance their understanding, and promote acquisition of the intended skills, knowledge, and attitudes.

Tanzania Institute of Education

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Dr Aneth A. Komba
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Chapter One

Cytology

Introduction

All living organisms are made up of units called cells. A cell is the basic structural, fundamental and functional unit of life. Understanding and learning about cells supports the learning of other biological processes. In this chapter, you will learn about the concept of cytology, cell theory, types of cells, and cell structure and function. You will also learn about cell differentiation, organic constituents of cells, and water as a constituent of the cell.

1.1 Concept of cytology

Cytology is the branch of biology that deals with the study of the structure and function of the cells. The cell is the basic structural and functional unit of all organisms. All living organisms may be composed of a single or many cells. The unicellular organisms consist of a single cell while multicellular organisms consist of multiple cells. For multicellular organisms, the cells are differentiated and organised into groups to form different structures that perform various functions.

Robert Hooke, who is also known as the father of cytology, was the first scientist to study the cell structure using a primitive microscope. In 1665, he examined a cross-section of the back of a cork tree and observed its structure (Figure 1.1). He found that the cork was made up of small chambers surrounded by walls; he gave the spaces the name "cell" meaning "little room" or "cavity". He thought the objects he had discovered looked like the individual rooms in a monastery, which were known as cells. The cells observed by Hooke gave no indication of the nucleus and other organelles found in most living cells. However, in his invention, Hooke did not discover the true biological function of cells.

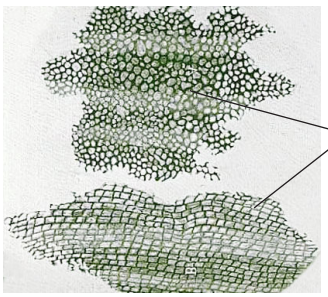


Figure 1.1 First view of the cork cells by Robert Hooke

Source: *http://ucmp.berkeley.edu*

He was later followed by Anton von Leeuwenhoek, who in 1674 discovered free living cells in pond water. Leeuwenhoek made a microscope consisting of a single high-quality lens which could magnify an object 270 times. This instrument was at that time referred to as a compound microscope. With this microscope, Leeuwenhoek was able to make a number of important scientific discoveries, including single-celled animals, plants, bacteria, and spermatozoa.

The importance of studying cytology

The study of cytology helps us to understand the role of cells as the building blocks of all living organisms, including their anatomy and physiology. Additionally, the significance of studying cytology includes the following:

a) Helps to realise the role of cells in metabolic processes such as respiration, protein synthesis, excretion, and growth.
b) Aids in understanding the detailed structure and functions of different cells.
c) Enhance an understanding on the structural (anatomical and chemical) composition of cells.
d) Gives knowledge about the process and significance of cellular differentiation, that is, a process in which cells are specialised for their functions, such as reproductive cells, red blood cells, absorptive cells, and nerve cells.
e) Enables us to understand how similar cells are organised into tissues.
f) Helps to show how organisms are evolutionarily related. For example, in the biochemical evolution theory of origin of life on the earth, various chemical compounds were combined and mobilized into prokaryotes, which gave rise to eukaryotes in the course of evolution.
g) Helps to understand the basis of genetics; the location, structure, chemistry, and role of nucleic acid (DNA and RNA).
h) Cytopathology, a study of cellular abnormalities, helps to diagnose diseases by using cellular changes.

1.2 The Cell Theory

The origin of the concept of "cell theory" can be traced to as 1830's when two scientists, Matthias Schleiden a Belgian botanist (1838) and Theodor Schwann, a German zoologist (1839) provided the first definition of the cell. It was stated that, all living organisms, both simple and complex, are made up of one or more cells. It was described that, the cell is the structural and functional unit of life. This led to the formation of the concept of cell theory. The theory states that "All living organisms are made up of cells". In 1855, Rudolf Virchow, a German physiologist, was among the first scientists to accept and extend the work of Robert Hooke. He showed that, the origins of cells was the division of pre-existing cells, and concluded that "new cells arise from pre-existing cells".

1.2.1 The main ideas of the cell theory

The principal ideas of the cell theory are as follows:

a) All living organisms are composed of one or more cells and cell products.

b) Cells are the basic or fundamental units of life, as all life processes are controlled by cells.
c) All new cells arise from pre-existing cells.

However, in the modern version of the cell theory, the following were added:

a) Cells contain genetic material which carry hereditary information (DNA) that is passed from one generation to another.
b) Energy flow occurs within cells in which all metabolic processes of life occur.
c) All cells have the same basic chemical composition, and the structure and functions of cells complement each other. The living organism's activities depend upon the combined actions of individual cells.
d) All new cells arise from pre-existing cells through cell division.

1.2.2 Shortcomings of the cell theory

Due to increased understanding on cell biology, the concept of "cell theory" has been challenged based on the modern knowledge of virology, blood cells and origin of life. The study of viruses indicated that these living infectious particles are non-cellular. Schleiden and Schwann could not explain the structure and functioning of a virus. They said that the body function is coordinated by the cell, which is not the case in a virus because it only starts its functioning when hosted by bacterial, plant or animal cell. Thus, as per the cell theory, they are non-living creatures (akaryotes). However, when they are in host cells, they exhibit living characteristics. Regarding the cell theory, there should be genetic material in every cell, but mature human red blood cells and sieve tube cells of angiosperm are some of the cells that lack genetic material. Furthermore, the cell theory revealed that new cells arise from the pre-existing cells by cell division. However, it does not show the origin of the first cell.

Exercise 1.1

1. Explain the importance of studying cytology.
2. Analyse the main ideas of the cell theory and its shortcomings.
3. Explain why the cell is regarded as the basic unit of life.

1.3 Types of cells

Based on the level of cell organisation, cells can be divided into two main types, namely prokaryotic cells and eurykaryotic cells. Prokaryotic cells have simple cell organisation, while eukaryotic cells have high level of cell organisation.

1.3.1 The prokaryotic cells

The word prokaryotes comes from two Greek words *pro* meaning 'primitive' or 'before' and *karyo (karyon)* meaning 'nucleus.' From this basic implication, prokaryotic cells refer to those cells which lack true or well organised nuclei such that the nuclear materials are freely suspended in the cytoplasm. The common examples of prokaryotic cells are bacteria and blue-green algae. Prokaryotic cells have the following general characteristics:

a) They are microscopic with an average diameter of 0.5-10 nm.

b) They lack well organised nuclei. That is, their nucleus has no nuclear membrane, therefore, the nuclear materials are freely suspended in the cytoplasm.

c) They have small, circular and naked DNA. That is, the DNA is not associated with histone protein coat to form chromosomes.

d) They have few and small ribosomes of 70s sedimentation coefficient.

e) They lack membrane bound organelles such as mitochondria, Golgi bodies, and plastids.

f) The cell wall is chemically composed of a carbohydrate-protein complex called peptidoglycan or murein.

g) Cilia and flagella, if present do not arise from basal bodies, and they lack microtubules of a "9+2" arrangement pattern.

Structure of prokaryotic cells

The prokaryotic cell does not have a defined nucleus, as it lacks a nuclear membrane. Almost all prokaryotes have a protective cell wall that prevents them from bursting in hypotonic conditions. Such cell walls have different components depending on the type of organism.

However, most of the prokaryotic cells have cell walls containing major organic molecules of proteins, carbohydrates and lipids. Bacterial cell walls have a unique molecule known as peptidoglycan. This component of the cell walls allows scientists to classify bacteria as either Gram-positive or Gram-negative. The Gram–positive bacterium contains many layers of peptidoglycan in the cell wall and lacks the outer membrane, while the Gram-negative bacterium contains a thin cell wall made up of a few layers of peptidoglycan and possesses the outer membrane.

The glycocalyx or capsule is a layer surrounding the cell wall of some bacteria. This layer protects the bacteria from drying out, especially in hypertonic conditions. The fimbriae are structures that help bacteria to adhere to target cells. They thus play a major role in bacterial virulence. The flagella are long whip-like extensions that help bacteria to move about in the environment. The axial filaments or endoflagella are long structures which move in waves enabling the bacteria to spin.

Beneath the cell wall, there is a plasma membrane, which is a double layer of phospholipids associated with proteins and other molecules. It protects the intracellular materials and regulates the movement of materials into and out of the cell. In some bacteria, there is infolding of the cell membrane that forms mesosome (which appeared to be associated with DNA during cell division, and also used in respiration), photosynthetic membrane (which contain photosynthetic pigment example bacteriochlorophyll used for photosynthesis) and or nitrogen fixing membrane (for nitrogen fixing bacteria). Beneath the cell membrane, there is cytoplasm, a gel-like fluid filling the cell. It is a place where cellular organelles such as ribosomes are suspended. Ribosomes (70s) are small structures in the cytoplasm that play crucial role in protein synthesis within the bacterial cell (Figure 1.2).

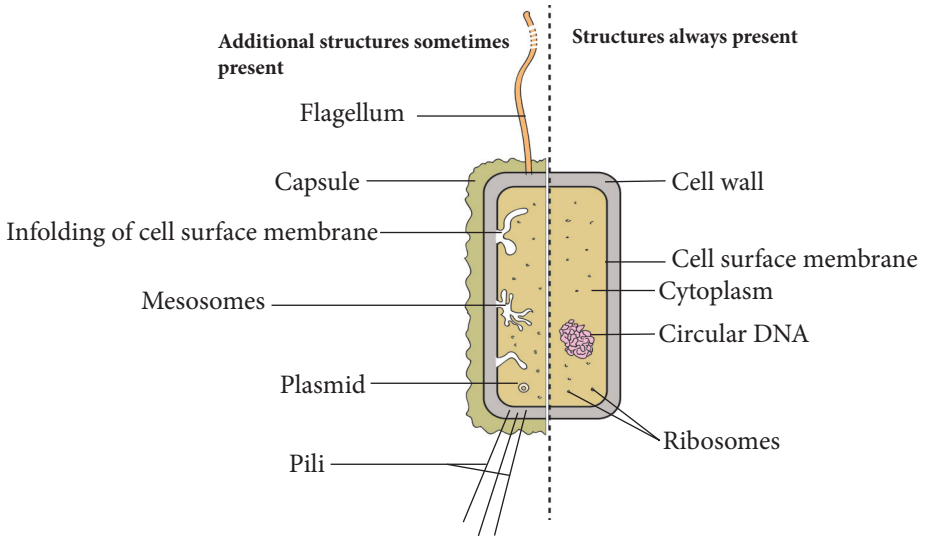


Figure 1.2 The structure of a typical prokaryotic cell

The prokaryotic cell consists of the nucleoid, a region of the prokaryotic cytoplasm containing the genome, which is the main genetic material (Figure 1.3). It possesses a single, circular DNA with a double-stranded DNA molecule. Some bacteria have additional genes located in small circular molecules of DNA called plasmids. These genes play roles in maintaining virulence to bacteria, for instance, by developing resistance to drugs. The resistant genes can be exchanged between bacteria through pili during conjugation process.

Most bacteria have a slender tubule-like structure on the cell wall called pili. There are two types of pili. The first type is used by related bacteria to exchange genetic material through the process of conjugation while the second type of pili enables bacteria to stick to their host or substrate which increases chances of infection.

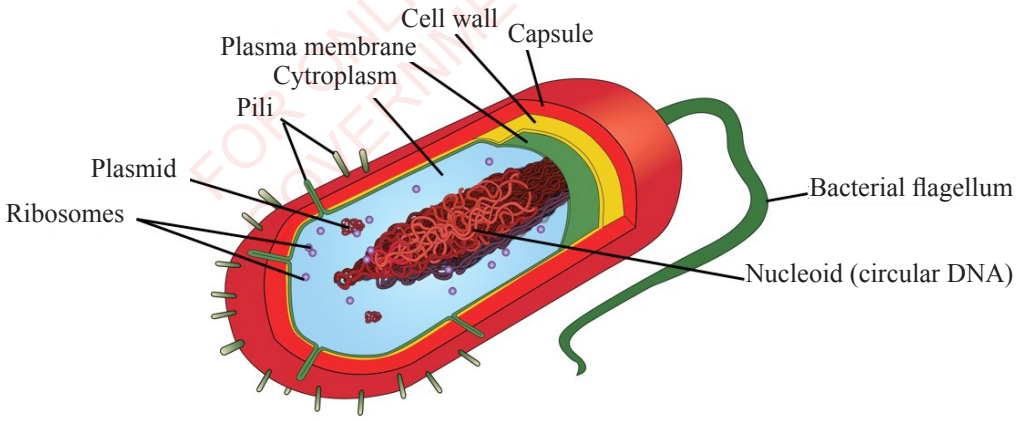


Figure 1.3 Structure of the rod shaped bacterium

Functions of parts of prokaryotic cells

a) The cell wall of prokaryotic cells provides structural and protective functions. In some prokaryotes, the cell wall is surrounded by a thin sheath, while in others, it is surrounded by a slim capsule.

b) The cytoplasm of prokaryotes is surrounded by a single cell membrane, and all metabolic processes such as protein synthesis, respiration, and replication take place within the cytoplasm.

c) Genetic material in the form of a single circular DNA located in the specified region within the cytoplasm. This controls hereditary functions of the cell.

d) The flagellum found in most aquatic and soil bacteria aids in movement by a unique process of spinning on an axis like a propeller.

e) The pili, a structure located on the cell wall help bacteria to increase the chances of survival by undergoing conjugation or by enabling anchoring to its host or substrate.

f) The mesosomes which are infoldings of the cell surface membrane which act as sites of respiratory enzymes.

g) Granules of food stores are used as respiratory substrates.

1.3.2 Eukaryotic cells

The term Eukaryote comes from two Greek words *eu* meaning 'true' and *karyon* meaning 'nucleus.' Eukaryotic cells are those cells whose nuclei are bounded by nuclear membranes. Cells are typically composed of plasma membrane, cytoplasm, nucleus, and organelles such as mitochondria, endoplasmic reticulum, ribosomes, and Golgi apparatus. The examples of eukaryotic cells are plant and animal cells. These cells are characterised by the following features:

a) They are relatively large in size, ranging from microscopic to macroscopic.

b) They have true or well organized nuclei with nuclear membranes.

c) They have large and numerous ribosomes with the sedimentation speed of 80s (The 's' stand for the name Svedberg, but is also a unit of measurement).

d) They have membrane bound organelles, such as mitochondria and plastids.

e) The cell walls, if present, are chemically composed of cellulose and/or chitin.

f) They have large, helical DNA which is associated with histone protein to form chromosomes.

g) Cilia and flagella, if present, arise from basal bodies and contain microtubules that are arranged in a "9+2" pattern.

The plant cell

Plant cells are eukaryotic and present in organisms of the kingdom Plantae. They have a true nucleus along with specialized structures called organelles that carry out different functions. Plant cells differ

from the cells of other organisms in that they have cell walls, chloroplasts, and central vacuoles. Therefore, the distinctive features of plant cells include the presence of cell walls containing cellulose, hemicelluloses and pectin, and the presence of chloroplasts capable of performing photosynthesis.

Structure of the plant cell

The general structure of the plant cell can be viewed by using an electron microscope (Figure 1.4). A plant cell has an outer layer surrounding the cell, called a cell wall. It is composed of cellulose, which is a stiff carbohydrate. The cell wall provides protection, structural support and mechanical strength to the cell. The presence of cellulose also helps the plant cell to maintain its regular shape. The cell wall has perforations that connect cytoplasm of the neighbouring cells called plasmodesmata. Beneath the cell wall, there is a cell membrane, which is semi-permeable. Cell membrane controls the passage of materials in and out of the cell. The adjacent cells are usually bound to one another by a thin layer called middle lamella.

The cytoplasm is a fluid content that fills the cell giving its shape; it contains proteins and dissolved ions used in cellular activities. It is a place where all cell organelles are housed. Most of the plant cells have large organelles called chloroplasts. Chloroplasts contain chlorophyll which is a green pigment used for photosynthesis. Other vital organelles found in the plant cells include mitochondria, endoplasmic reticulum, ribosomes and golgi vesicles. Mitochondrion acts as a powerhouse of the cell; because it releases energy used for all cell activities.

The Endoplasmic Reticulum (ER) is a large folded membrane system found in the cytoplasm of the cell. Some ER are associated with ribosomes while others are not. The ER that are associated with ribosomes are known as Rough Endoplasmic Reticulum (RER), whereas those not associated with ribosomes are known as Smooth Endoplasmic Reticulum (SER).

Ribosomes are the organelle responsible for protein synthesis within a cell. Hence, the RER provides a surface for protein synthesis while the SER provides a surface for transportation of liquids and nutrients in the cell. There are small vesicles in the cytoplasm called Golgi vesicles. These are responsible for storage and transportation of secretions of the cells. In addition, the plant cell has a large central vacuole which is responsible for storage of nutrients and water. The nucleus is a vital part of the cell, as it controls all cell activities such as growth, cell division, DNA replication and its transcription to RNA. It also contains hereditary material which transmit traits from parents to the offsprings.

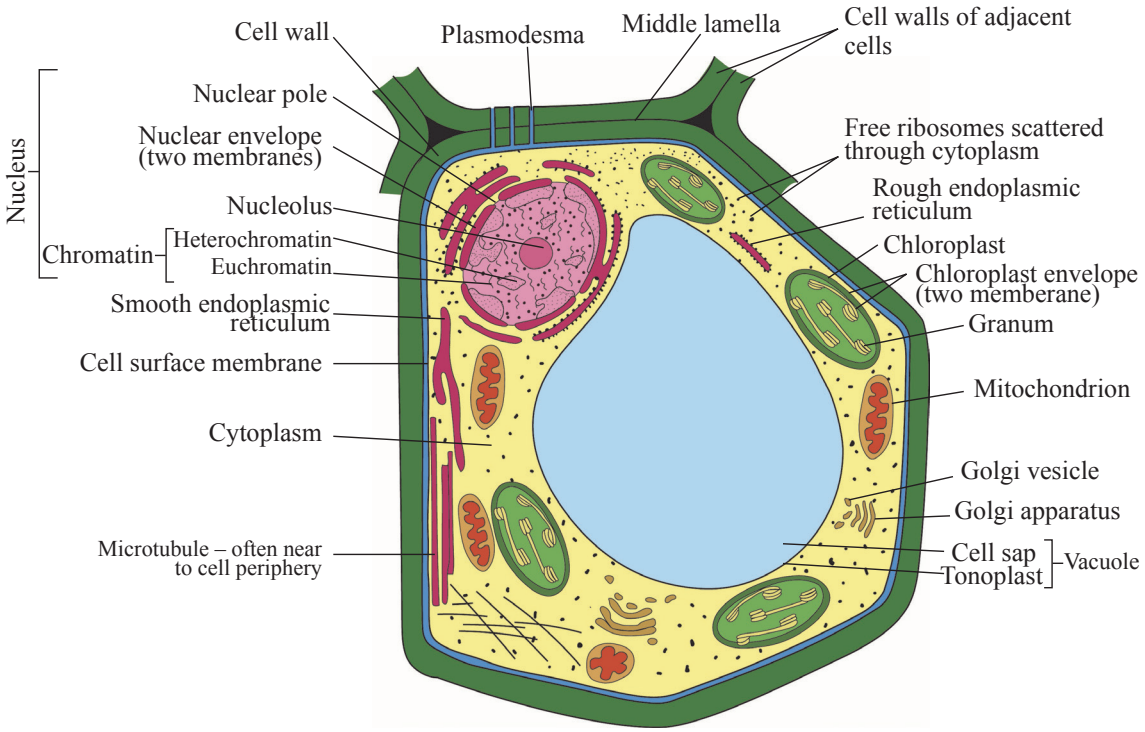


Figure 1.4 A generalised structure of a plant cell as seen under electron microscope

Activity 1.1 Observation of a plant cell under a light microscope

Materials

Onion bulb, a light microscope, microscope slide, slide cover, petri dish or watch glass, iodine solution, water, forceps, a needle, and a knife or surgical blade or scalpel.

Procedure

a) Slice the onion longitudinally into small parts by using a knife or scalpel.

b) Using forceps, remove the thin transparent inner lining.

c) Put a specimen on a watch glass or petri dish containing some water to prevent shrinking.

d) Mount the specimen at the centre of the microscope slide.

e) Add a drop of iodine solution.

f) With the help of a needle, place the cover slip gently. Make sure there are no air bubbles under the cover slip.

g) Observe the specimen under the light microscope at low, medium, and high power objectives. The images tend to be smaller under low power objective lens. However, if more magnification is needed, change objective lenses to medium and high power. Structures such as nucleus, cytoplasm, chloroplasts, vacuole, cell wall, and cell membrane can be clearly seen.

Question

Draw what you have observed and compare your diagram with that of Figure 1.4.

Safety precaution

Be careful when working with sharp objects such as needle, knife and surgical blade.

The animal cell

Animal cells are eukaryotic cells with a membrane bound nucleus. Unlike the eukaryotic cells of plants and fungi, animal cells do not have a cell wall. Animal cell comprises of different cell organelles and cell structures which perform specific functions necessary for the cell. The cell organelles have a vast range of functions to perform. The animal cells contains centrioles, endoplasmic reticulum, Golgi apparatus, lysosomes, microfilaments, microtubules, mitochondria, nucleus, peroxisomes, plasma membrane, ribosomes, cilia, and flagella.

Structure of the animal cell

The outer boundary of the animal cell is a cell membrane; which is selectively permeable to substances and controls the exchange of materials between the cell and its environment. Beneath the cell surface membrane, there is a protoplasm which is made up of cytoplasm and the nucleus (Figure 1.5). Like in the plant cell, the cytoplasm of the animal cell is jelly-like fluid filling the cell and it houses all cell organelles. The cytosol or cytoplasmic matrix is a fluid found in the cell organelles, such as mitochondria and ribosomes. The cytosol is a site of metabolic activities in the cell organelles. Mitochondria are called the powerhouses of the cell; since they release energy in the form of ATP through the process of respiration. The produced energy is used to run metabolic activities of the cell. The nucleus is the central part containing the hereditary (genetic) material. It also controls cell activities such as growth, cell division, DNA replication, and protein synthesis.

Ribosomes are the smallest organelles responsible for protein synthesis in the cell. Some ribosomes are located on the surface of the endoplasmic reticulum which is a large folded membrane system in the cytoplasm. Like plant cell, animal cell has rough endoplasmic reticulum and smooth endoplasmic reticulum. Moreover, the animal cell has small vesicles in the cytoplasm known as Golgi vesicles which are responsible for the storage of enzymes and formation of lysosomes. Lysosomes are small structures in the cytoplasm which contain digestive juices responsible for breaking down of old cell parts. There are also long structures called microtubules or microfilaments. These are responsible for all cell movements, and they provide the cell with cytoskeletal support.

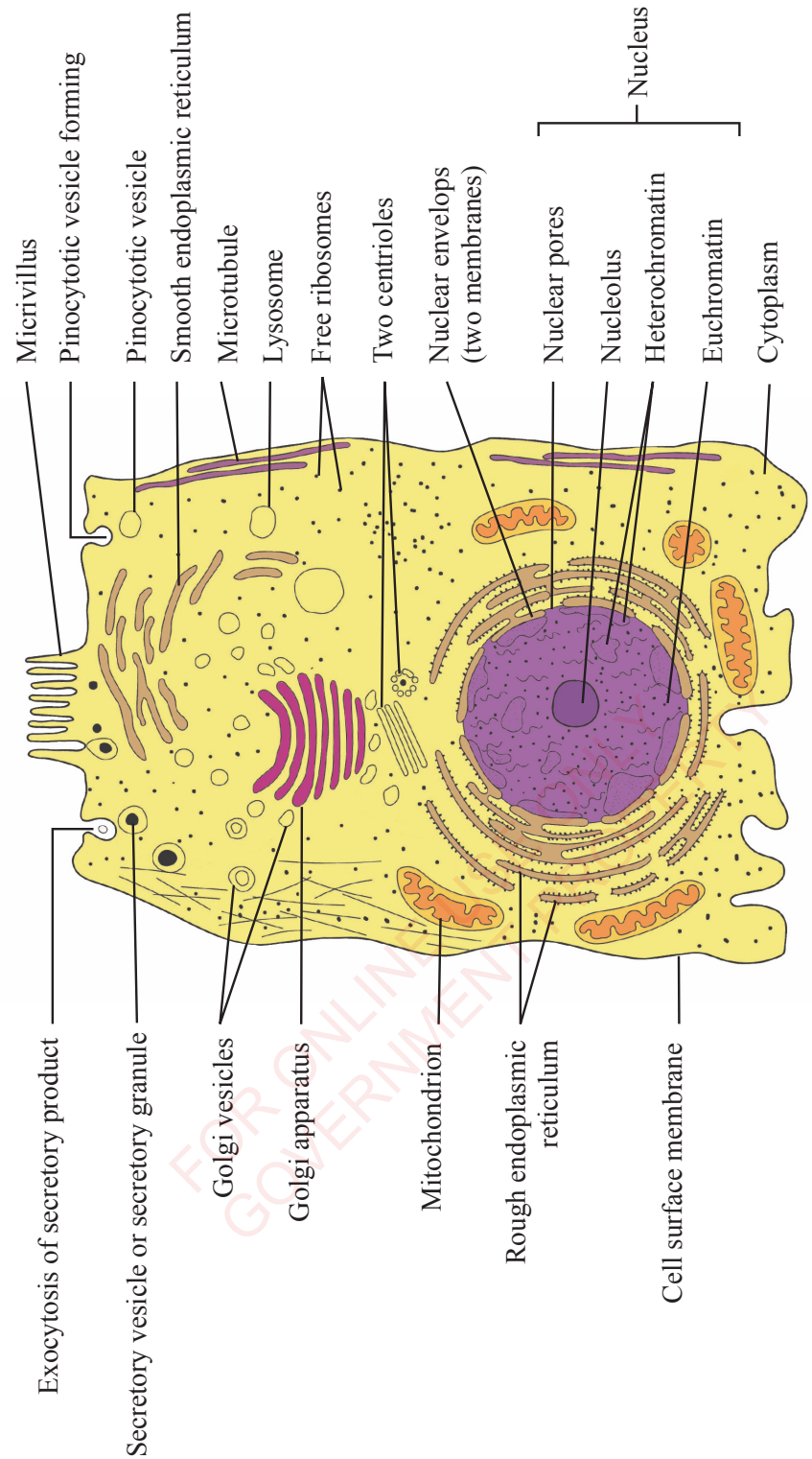


Figure 1.5 A generalised structure of animal cell as seen under electron microscope

Activity 1.2 Observation of an animal cell under a light microscope

Materials

A plastic spoon, a light microscope, slides, cover slips, a needle, and methylene blue.

Procedure

a) Gently scrub the inside of your cheek with a plastic spoon to obtain a cell sample. Plastic spoons are used to avoid damaging the cheek cells.

b) Place the cheek cells sample on a clean slide.

c) Add a drop of methylene blue and mix using a pointed needle.

d) Cover the specimen with a cover slip. Make sure that there are no air bubbles under the cover slip.

e) Observe the specimen under the light microscope at low, medium, and high power objectives. You will see that, at the low power objective, the cells appear very small; in contrast, at the high power objective, they appear to be relatively larger.

Question

Draw what you have observed and compare your drawing with that of Figure 1.5.

Safety precautions

1. Be careful when working with sharp objects such as needle, knife and surgical blade.
2. Do not share instruments used to obtain cell sample.

Exercise 1.2

1.a) Draw and label the structure of plant and animal cells as they are seen under high power magnification of light microscope.

b) Compare and contrast the two cells in (a) above.

2. Describe the composition of cell cytoplasm and its functions.

3. Explain how the discovery of the electron microscope improved knowledge on cell structure.

4. Describe the contribution of each of the following scientists in cell biology:

a) Robert Hooke (1665).

b) Theodor Schwann and Mathias Schleiden.

Structure and functions of the cell

In general, a cell consists of cell membrane, the nucleus and the cytoplasm. Every cell in the body is enclosed by a cell membrane. The cell membrane is the protective barrier that surrounds the cell, which separates the material outside the cell (extracellular), from the material inside the cell (intracellular). It is the barrier that maintains the integrity of a cell and controls passage of materials into and out of the cell. Apart from cell membrane, other cells such as plant and fungal cells have an additional outer layer called a cell wall. It is formed on the outside of the

cell membrane to give the cell an extra support, protection, as well as efficiency and regulates exchange of materials.

The nucleus is the largest cellular structure, located inside eukaryotic cell and acts as the control centre of a cell. The material between the cell membrane and the nuclear envelope is known as cytoplasm. Within the cytoplasm lies an intricate arrangement of fine fibres and thousands of miniscule but distinct structures called cytoplasmic organelles and cytoplasmic inclusion such as stored nutrients, secretory products, droplets and pigment granules. Cytoplasmic organelles are small structures that are suspended in the cytoplasm of the cell. Examples of cytoplasmic organelles include: endoplasmic reticulum, ribosomes, mitochondria, plastids, vacuole, lysosome, microbodies, cytoskeleton, and Golgi apparatus. Each type of organelle has a definite structure and a specific role in the cell. Cytoplasmic inclusions do not have any membrane or specific shapes.

Plasma membrane

This is also called plasmalemma or cell membrane. It surrounds most of the cell organelles, separates the contents of the cell from the external environment, and controls the exchange of materials. In animal cells, plasma membrane is the outermost layer, whereas in plant cells it is located beneath the cell wall.

Structure of the cell membrane

The cell membrane is made up of proteins and lipids (phospholipids). Protein molecules are embedded in the layers of the phospholipids. Phospholipids form a bilayer structure which is fundamental to the selective permeability function of the membrane. Each phospholipid molecule consists of a hydrophobic (water hating) tail of two fatty acids and the hydrophilic (water loving) phosphate head. In the cell membranes, phospholipids arrange themselves in a layer of two molecules thick (bilayer), with their hydrophobic tails pointing inwards, away from the water both inside and outside the cell, while the hydrophilic heads face outwards. There are two models suggested to describe the structure of the plasma membrane, namely Danielli-Davson's model (1935) and Fluid Mosaic model (1972).

Danielli-Davson's Model

According to Danielli and Davson, the membrane is structurally composed of two chemical substances made up of proteins and lipids that form trilaminar layers (Figure. 1.6). The outer and inner layers are made up of protein molecules which sandwich the phospholipids bilayer. The heads of phospholipids are polar, oriented towards the protein layers to form the hydrophilic region.

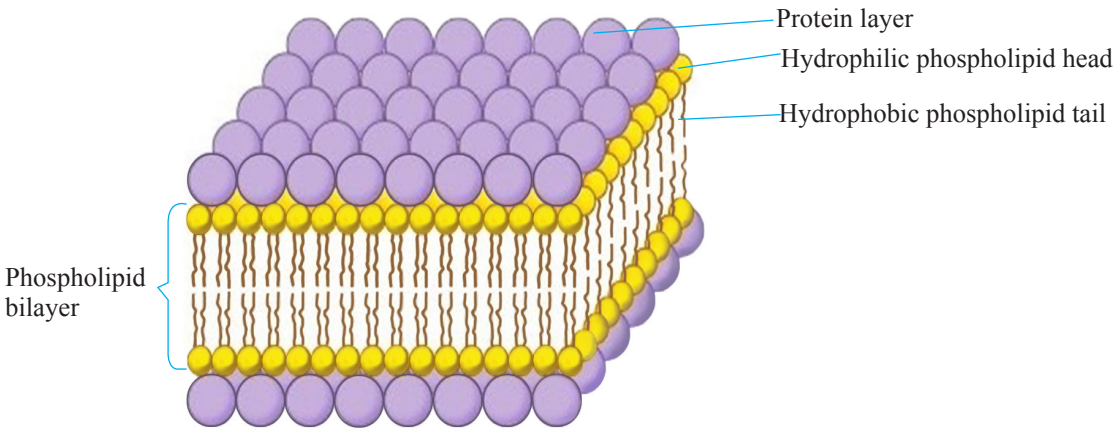


Figure 1.6 Model of plasma membrane as proposed by Daniel and Davson

The model explains the presence of polar head (hydrophilic) and non-polar tail (hydrophobic) in the phospholipids. The proteins bilayers are continuous and are of the same size. The model did not explain how material enters or leaves the cell. The model also indicate that the membrane is static, never change its structure and water passes freely between the adjacent protein molecules. The protein bilayers are on the outside part, while phospholipids bilayers are at the middle part (intermediately). The model explains the presence of proteins and phospholipids. Moreover, this model does not explain how cell recognizes external signals and due to this weakness, further studies were conducted and a new model was developed. This was the Fluid Mosaic Model.

The Fluid Mosaic Model

The model was proposed by Seymour J. Singer and Garth L. Nicolson in 1972. According to this model, protein molecules are dispersed and inserted into a phospholipid bilayer, which is hydrophilic when exposed to water (Figure 1.7). This provides maximum contact of hydrophilic regions and heads of phospholipids with water while providing the hydrophobic part with a non-aqueous environment. Due to the fluid nature of phospholipids and the arrangement pattern of protein molecules in the phospholipid bilayer, the model is referred to as the Fuid Mosaic Model.

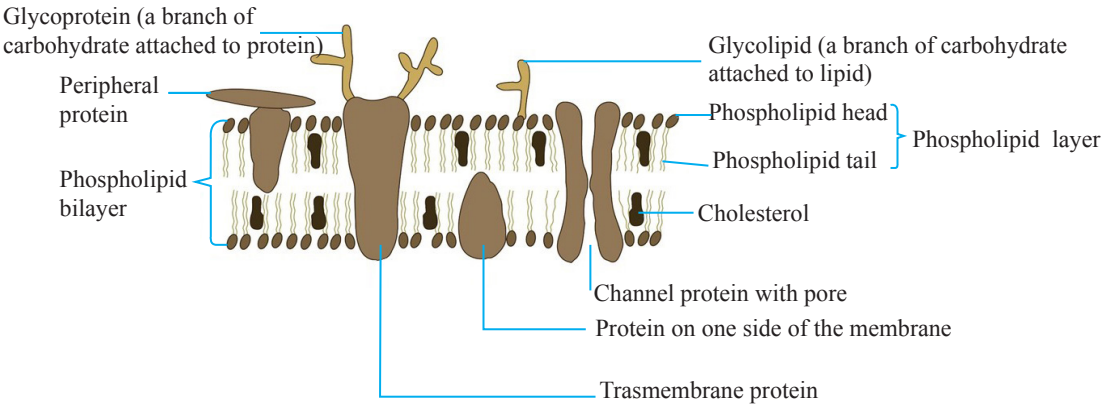


Figure 1.7 Structure of a plasma membrane as per Fluid Mosaic Model

Lipids and lipid-soluble substances are allowed to cross the hydrophobic region while non-lipids are not allowed to cross. Large molecules, such as glucose, fatty acids, glycerol and amino acids are repelled by the hydrophobic region and therefore, they diffuse through special transport proteins called channel proteins and carrier proteins by facilitated diffusion.

The strength of the model is that, it realizes the presence of the phospholipid bilayer and protein layer. It also realizes the presence of pores in the membrane and the presence of cholesterol in the membrane. The model explains the presence of polar head (hydrophilic) and non-polar (hydrophobic) tail in phospholipids. Furthermore, the model explains the presence of glycolipid, as receptors that allow the cell to respond to chemical messengers which regulate the activities of the cell. It is true that the membrane is a dynamic (ever-changing its structure) with phospholipids in constant motion. The weakness of the model is that it does not indicate or explain the presence of electrolytes in the plasmalemma.

Functions of the plasma membrane

a) It covers the surface of every living cell and acts as a barrier which separates the cytoplasm from extracellular environment.
b) It allows passage of some materials in and out of the cells (selective permeability).
c) It facilitates the transmission of nerve impulse in the nervous system.
d) It functions as a receptor site for hormonal and neural transmission of chemical stimuli.
e) It aids cell-to-cell recognition when membranes of two cells come together.
f) It serves as a base for attachment of the cytoskeleton in some organisms and as the cell wall in others. Thus, the cell membrane supports the cell and maintains its shape.

Adaptations of the cell surface membrane

The cell membrane is specialised to its functions due to:

a) Presence of glycolipids, glycoproteins and phospholipids for detection of stimuli, such as antigens and antibodies.

b) Presence of hydrophilic pores for passage of polar substances.
c) The phospholipid bilayer facilitates the passage of fat soluble substances.
d) Presence of microvilli increases the surface area for absorption.
e) Presence of proteins with specific shapes makes the membrane a receptor site for chemical stimuli such as hormones.
f) Presence of glycolipid and glycoprotein enable the membrane to bind to the membrane of a neighbouring cell, that is, cell-to-cell recognition.
g) Presence of cholesterol disturbs the close packing of phospholipids. This keeps them more fluid and maintains stability and flexibility of the membrane over a wide range of temperature.

Exercise 1.3

1. Describe the structure of a plasma membrane as proposed by Danielli-Davson model.
2. Describe the structure of a cell membrane as envisaged by Jonathan Singer and Garth Nicolson in the Fluid Mosaic Model.
   a) Explain why membranes are generally referred to as fluids.
   b) Name the chemical constituents of membranes and enumerate the role of each.
3. How is the cell membrane adapted to its function?

Cell wall

Plant cells, fungal cells, and bacterial cells are surrounded by fairly rigid, non-living walls called cell walls (Figure 1.8). The chemical composition of cell walls among these organisms differs. The plant cell wall is made up of cellulose. The fungal cell wall is made up of chitin. The bacterial cell wall, is made up of peptidoglycan called murein.

A cell wall is a protective layer around the plasma membrane. It also determines the shape of plant cells. Originally, the cell wall in plants is a product of cytoplasm. The cytoplasmic organelles such as the endoplasmic reticulum and Golgi apparatus play a very important role in the formation of cell walls. The formation of a new cell wall usually takes place in a dividing cell immediately after the nuclear division.

Structure of the cell wall

Plant cell wall, which is made up of cellulose and strengthened by other polysaccharides; is a protective layer around the cell surface membrane. The primary cell wall in plants is composed of cellulose, hemicelluloses and pectin. This primary wall is laid down during cell division in plants. The primary cell wall thickens into secondary cell wall. During secondary thickening some cells undergo lignification (hardening) whereby lignin is deposited in all cellulose layers. Lignin cements and anchors fibres together, making the cell wall very hard and increases tensile strength. Suberin and cutin are also found in the cell wall during secondary thickening. These are waxy materials acting as a water proof coat

which helps to prevent excessive water loss from the plant. Middle lamella is a thin layer of pectin materials (calcium and magnesium) which joins neighbouring cell walls together.

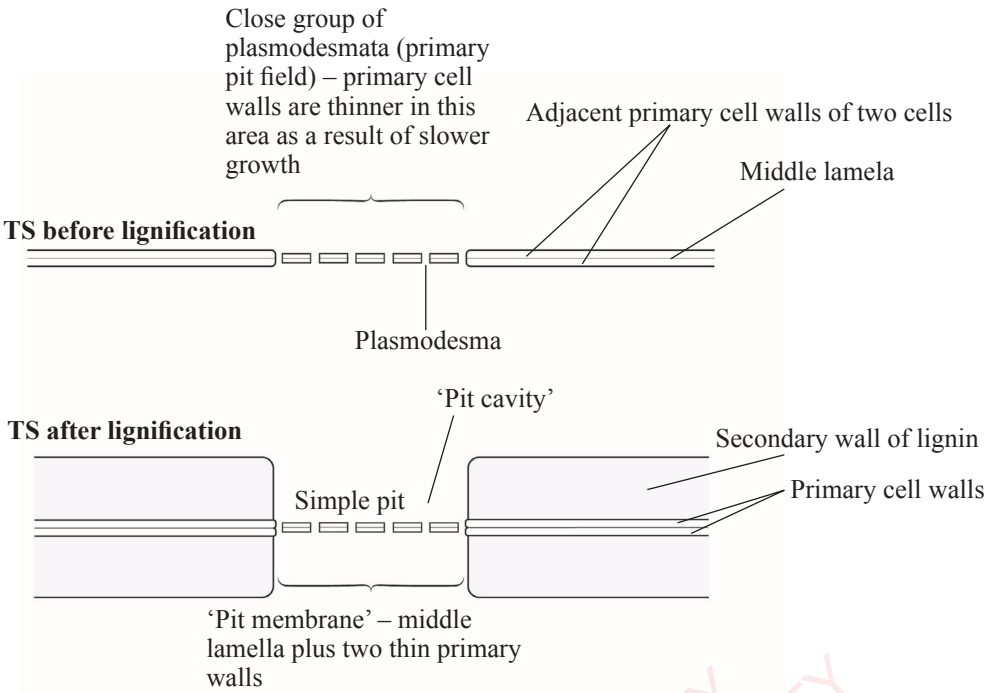


Figure 1.8 Structure of a cell wall

Functions of the cell wall

a) It provides mechanical support and strength to cells and the plant as a whole, due to presence of lignin.

b) It maintains the shape of the cell, since the cell wall is rigid.

c) It prevents the osmotic bursting of the cell by inhibiting excessive endosmosis due to its capability to resist expansion.

d) It protects the plant cells against pathogens and water loss due to the presence of waxy cutin on the cell wall.

e) The walls of xylem vessels, tracheids and phloem sieve tubes are tubular; therefore, they allow movements of materials to long distances.

f) Cell walls possess small pores or pits through which the materials can pass from one cytoplasm to another (symplastic movement).

g) Cutin and suberin deposits prevent loss of water from the cell surface through evaporation.

h) The cell walls of root endodermal cells are suberized to form casparian strips. These, among other functions, regulate the amount of water to be admitted into the plant.

i) Cell walls of some cells store food.

Exercise 1.4

1. Describe the composition of the cell wall in living organisms.
2. Explain the functions of lignin and suberin in the plant cell.
3. Give the name of the structure which joins neighboring cell walls.

Cytoplasm and cytoplasmic organelles (sub-cellular units)

The space between the cell membrane and the nucleus is filled with translucent, homogenous and colloidal fluid called a cytoplasmic liquid. The latter is an aqueous substance containing different types of cell organelles, water and mineral salts. It also contains organic compounds, such as carbohydrates, lipids, proteins, nucleic acids and enzymes.

Functions of cytoplasm

a) It provides medium for chemical reactions such as glycolysis to take place.
b) It stores useful materials such as starch, glycogen, and lipids.
c) It stores waste materials such as nitrogenous wastes.
d) Movement of materials takes place within the cytoplasm.
e) It harbours and organises cell organelles that perform different functions such as protein synthesis in ribosomes and lipid synthesis in smooth endoplasmic reticulum.

Cytoplasmic organelles

Cytoplasmic matrix contains numerous membranous internal structures called organelles. Organelles can be defined as tiny distinct parts with specialised structures and functions found inside the cell. The organelles are sub-cellular structures with characteristic morphological forms, distinctive chemical constitutions and definite functions. The organelles perform specific functions such as oxidative phosphorylation and generation of energy in the form of ATP in the mitochondria, formulation and storage of carbohydrates in chloroplast, protein synthesis in ribosomes of the rough endoplasmic reticulum and concentration and packing secretions in Golgi apparatus. Other functions include synthesis of lipid and hormones in smooth endoplasmic reticulum, degradation of macromolecules in the lysosomes, regulation of all cellular activities by nucleus, and organisation of spindle apparatus by centrioles.

The nucleus

The nucleus is a functional unit of a cell. It is a membrane-bound structure, located at the periphery of the cell membrane more or less to the centre of the cell and it contains the cell's hereditary information. It controls all cellular activities and is the most prominent organelle in the cell. The cell nucleus is bounded by a double membrane called the nuclear envelope. It is a selectively permeable membrane, allowing some materials to pass in and out and separates the contents of the nucleus from the cytoplasm. The envelope regulates the flow of molecules into and out of the nucleus through nuclear pores. The pores allow exchange of substances between

the nucleus and cytoplasm. The pore has a definite structure formed by fusion of the outer and inner membranes of the envelope. The nucleus contains chromatin, consisting of DNA which is bounded by basic proteins called histones. During nuclear division, chromatin stains more intensely and becomes more conspicuous because it condenses into more tightly coiled threads called chromosomes. However, some remains tightly coiled and continue to stain intensely and this is called heterochromatin. It is seen as a dark patch, usually occurring near the nuclear envelope. The remaining loosely coiled chromatin is euchromatin. It contains DNA which is genetically active during interphase.

The nucleolus

The nucleolus is a cellular structure present in the nucleus of a eukaryotic cell. The nucleolus appears as a rounded and darkly stained structure inside the nucleus. It contains nucleolar organisers that synthesise ribosomes by transcribing and assembling ribosomal RNA (Figure 1.9). The nucleoli vary in number from one to many nucleoli within a single cell nucleus of a plant or an animal cell.

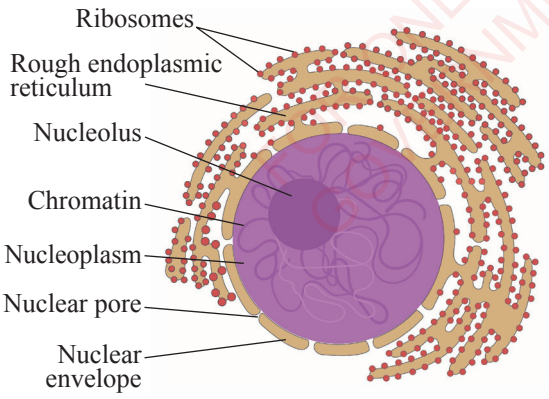


Figure 1.9 Structure of a nucleus

Functions of the nucleus

a) It controls all metabolic activities of the cell.

b) It contains hereditary information of the cell, hence, it transmits genetic information to the new cell.

c) It takes part in the formation of ribosomes and RNA, thus it controls protein synthesis.

d) It controls cell division when required since DNA replication is essential for cell division.

Exercise 1.5

1. Describe the structure of the nucleus of a cell.
2. Explain the role of nucleolus.
3. Why is the nucleus said to be the controller of all cellular activities?

Endoplasmic reticulum

The endoplasmic reticulum is a network of flattened membranes bound sacs called cisternae. Some of the endoplasmic reticula are encrusted with ribosomes and termed Rough Endoplasmic Reticula (RER), while those without ribosomes are known as Smooth Endoplasmic Reticula (SER). The quantity of both rough and smooth endoplasmic reticula in a cell can slowly interchange from one type to the other, depending on the changing metabolic activities of the cell.

Rough endoplasmic reticulum (RER)

The surface of the rough endoplasmic reticulum contains protein-manufacturing ribosomes, giving it a "rough" appearance

(Figure 1.10a). However, the ribosomes bound to it at any one time are not a stable part of this organelle's structure as they are constantly being bound and released from the membrane. A ribosome only binds to the endoplasmic reticulum once a specific protein-nucleic acid complex forms in the cytosol. This special complex forms when a free ribosome begins to translate the mRNA.

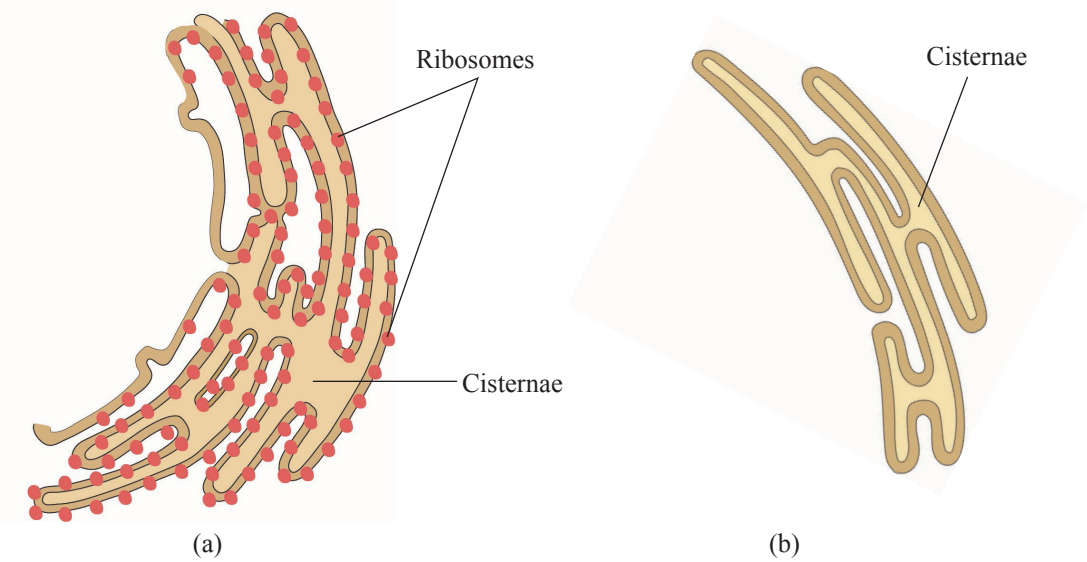


Figure 1.10 The structure of endoplasmic reticulum (a) RER (b) SER

Functions of rough endoplasmic reticulum

The rough endoplasmic reticulum has the following functions:

a) They are sites for protein synthesis, due to the presence of ribosomes.

b) They provide pathways for transportation of materials through the cell, such as proteins synthesized on the ribosomes.

c) They provide a large surface area for chemical reactions to take place.

Smooth endoplasmic reticulum (SER)

This type of endoplasmic reticulum possesses smooth walls, because the ribosomes are not attached to its membranes (Figure 1.10b). The smooth endoplasmic reticulum occurs mostly in those cells which are involved in metabolism of lipids such as steroids and glycogen. The smooth endoplasmic reticula are generally found in adipose cells, interstitial cells, and glycogen storing cells of the liver. They also occur in conduction fibres of the heart, spermatocytes and leucocytes. The muscle cells are also rich in smooth endoplasmic reticulum known as the sarcoplasmic reticulum.

Functions of smooth endoplasmic reticulum

a) For synthesis, secretion, and storage of lipids, carbohydrate and other non-protein products.

b) It contains enzymes which breakdown chemical substances in liver cells.

c) For synthesis of steroids which later form hormones.

d) It increases the surface area for chemical reactions in the cell to take place.
e) It is involved in the formation of Golgi bodies.

Exercise 1.6

1. Describe the structural differences between smooth and rough endoplasmic reticulum.
2. Outline the functions of endoplasmic reticulum.
3. Explain how the RER and SER are adapted to their roles.

Mitochondrion

A mitochondrion (plural mitochondria) is an organelle bound by double membranes and it is found in eukaryotic cells. Mitochondria have been described as 'the powerhouses of the cell' because they generate most of the cell's chemical energy originally contained in respiratory substrates. This energy is liberated in the form of adenosine triphosphate (ATP).

The structure of the mitochondrion

Each mitochondrion is bounded by two highly specialised membranes. Thus, it is a double membrane organelle. The outer membrane is quite smooth, it has many copies of a transport protein called porins, which forms large aqueous channels through the lipid bilayer. On the inside is the inner membrane separated from the outer membrane by a space, measuring 6 - 8 nm. The inner membrane is deeply folded into infolding known as cristae, which project in the matrix space.
Generally, the organelle has an oval shape, although it can change from one form to another depending on the physiological conditions of the cells. The matrix contains few small ribosomes (70s), phosphate granules, respiratory enzymes (such as ATP synthase) and small mitochondrial DNA which is circular and naked (Figure 1.11).

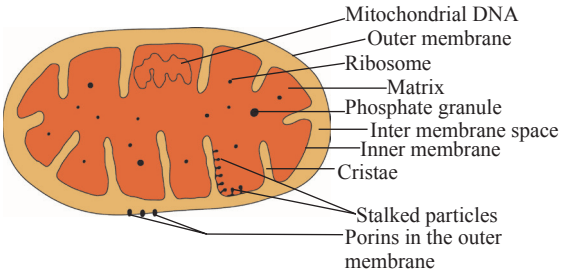


Figure 1.11 A structure of a mitochondrion

Functions of mitochondria

a) It is a site for aerobic respiration, hence releases energy in the form of ATP.
b) It is an intermediate site for synthesis of important biomolecules such as chlorophyll, cytochromes, steroids, and fatty acids.
c) The mitochondrion can store and release calcium ions when required. Hence, it regulates calcium ion concentration in the cell.

Adaptations of mitochondria

The mitochondrion is specialised to its function because:
a) The outer membrane contains lots of porins that allow the passage of molecules for respiration.
b) The inner membrane is highly folded into cristae that increase its surface area.
c) The membranes are permeable to allow the passage of all diffusable

materials. This allows raw materials in and products out.

d) The matrix contains appropriate enzymes used in respiratory pathways such as Kreb's cycle.

a) Presence of windows or fenestra in the membranes facilitates the passage of materials in and out.

Plastids

These are membrane bound organelles found in the cells of plants, algae, and other eukaryotic organisms. They often contain pigments and the type of pigment determines the cell colour. They are mainly responsible for activities related to making and storing food. The plastids include chromoplasts, gerontoplasts, leucoplasts, and chloroplasts.

Chromoplasts. Pigmented plastids found in flowers, aging leaves, and fruits such as tomato and red pepper. They contain carotenoid pigments; mainly red, orange or yellow which give different colours seen in different parts of the plant. They assist in pollination and seed dispersal.

Gerontoplasts. Plastids that develop from the chloroplasts of the leaves or other parts of the plant that are going through the ageing process (senescence) or are converted into different organelles. This occurs when such parts of the plant are no longer carrying out photosynthesis.

Leucoplasts. Colourless plastids found in non-photosynthetic parts of the plant such as roots, seeds, and bulbs. They are used for storage of starch, lipids, and proteins particularly in roots and tubers. They are subdivided into three different types, namely amyloplasts, proteinoplasts, and elaioplasts. Each of these has a distinctive function. For instance, amyloplasts are responsible for storage of starch, proteinoplasts are responsible for storage of proteins, while elaioplasts are responsible for storage of fats and oils which are needed by plants. They are also used for synthesis of amino acids and fatty acids.

Chloroplasts. These are most commonly known plastids which play an essential role in enabling plants and some algae to make their own food through photosynthesis. They are found in green parts of plants, mainly leaves and in some other organisms such as photosynthetic bacteria and green algae. The term chloroplast comes from two Greek words: *chloros,* meaning 'green' and *plast,* meaning 'form'. It contains green pigment known as chlorophyll, enzymes and other molecules that function in photosynthesis.

Structure of chloroplasts

The contents of chloroplasts are portioned from the cytosol by an envelope consisting of two membranes separated by a very narrow inter-membrane space. Inside the chloroplast is another membranous system in the form of flattened sacs called thylakoids or lamellae. In some regions, thylakoids pile up like a stack of coins to form grana (singular, granum). The fluid outside the thylakoids is the stroma, which contains the chloroplast DNA, ribosomes (70s), starch granules as well as many photosynthetic enzymes. The chlorophyll and carotenoids are present in thylakoids and grana (Figure 1.12).

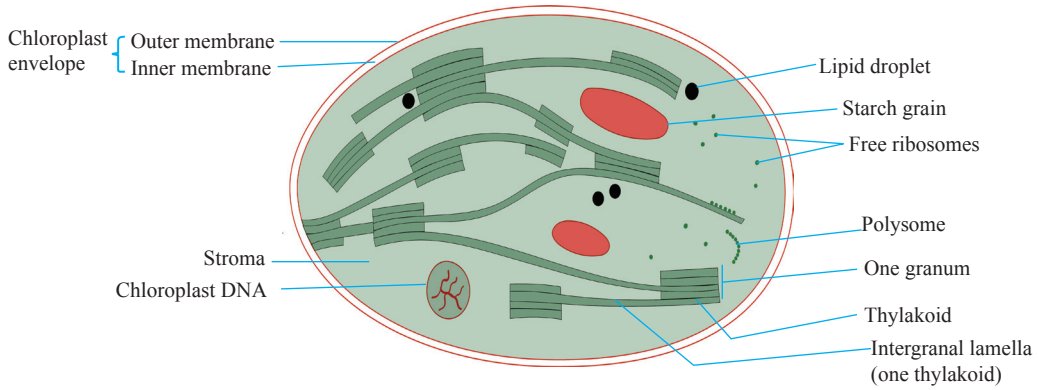


Figure 1.12 Structure of the chloroplast

Functions of the chloroplast

a) The chloroplast is the fundamental site for the photosynthesis process.

b) It is the site for protein synthesis, due to the presence of ribosomes in the stroma.

c) It stores starch and lipids for plant use.

Adaptation of the chloroplasts

Chloroplasts are specialised for their function as follows:

a) They have permeable membranes which allow movement of raw materials in and products out.

b) The presence of numerous grana provides a large surface area for photosynthetic pigments, electron carriers and ATP synthase involved in the light dependent reaction.

c) Arrangement of photosynthetic pigments in photosystems allows maximum absorption of light energy.

d) Proteins embedded in the grana hold photosystems and their chlorophyll in proper position for harvesting light.

e) The stroma contain enzymes needed to catalyse the reactions in the light independent phase of photosynthesis.

f) Contains chloroplast DNA for self-replication and inheritance.

g) They have ribosomes needed for protein synthesis.

Exercise 1.7

1. What are the differences between mitochondria and chloroplasts?
2. Explain why chloroplasts and mitochondria are considered as prokaryotic cells in the eukaryotic cells.
3. Draw and label a diagram of each of the following organelles:
   a) Chloroplast
   b) Mitochondrion

Vacuoles

Vacuoles are membrane bounded sacs which are found within the cytoplasm of a cell. The vacuoles of plant cells are bounded by single membranes called tonoplast. These vacuoles are formed when vesicles released by the endoplasmic reticulum and Golgi apparatus merge together. Young plants consist of a number of smaller vacuoles which during growth and development, they fuse to form a large central permanent vacuole. Therefore, in a mature plant cell, cytoplasm is displaced and seen as a thin layer near the periphery of the cell surrounding the large central vacuole. The central positioning of the vacuole push the nucleus more or less to the periphery or near to the cell surface membrane. At this stage, the vacuole is filled with cell sap, which contains water, phenol, mineral salts, alkaloids, pigments, sugars, and proteins. Animal cell lack vacuoles, but if present they are small and temporary, associated with storage of food and other materials to be secreted, transported or removed. Example, food vacuole or vesicle (phagocytotic or pinocytotic vesicles).

Functions of vacuoles

Vacuoles in plant cells play the following roles:

a) They support herbaceous plants and herbaceous parts of woody plants by providing an osmotic system which creates a pressure potential.

b) They act as temporary stores for different substances, such as food, enzymes, and waste materials.

c) They have hydrolytic enzymes which destroy dead cells or the entire plant cell (autolysis). Plant vacuoles can function in the same way as in lysosomes of animal cells as they both participate in an automatic cell death by autolysis. This process occurs when the tonoplast ruptures and releases its contents (enzymes) into the cytoplasm which digests the entire cell.

d) They play vital role in primary growth, since the pressure exerted by fusion of small vacuoles leads to elongation of the cells. Hence, this increases the length of a plant organ.

e) They contain anthocyanins which provide colour to flowers, fruits, and buds. These pigments facilitate pollination and seed dispersal.

Ribosomes

Ribosomes are tiny organelles found in the matrix of mitochondria, chloroplasts, and cytoplasm of the cells. They occur in both, prokaryotic and eukaryotic cells. In prokaryotic cells they are found freely in the cytoplasm, whereas in the eukaryotic cells they are either attached to the outside of the endoplasmic reticulum (or nuclear envelope) or occur freely in the cytoplasm. Structurally, each ribosome is made up of two sub-units, a small sub-unit and a large sub-unit (Figure 1.13). Basing on their size and sedimentation coefficient, there are two types of ribosomes. These are:

a) 70s ribosomes: These are relatively smaller, with sedimentation coefficient of 70s and molecular weight of $2.7x10^6$ Daltons. They occur in prokaryotic cells, such as in blue-green algae and bacteria.They also occur in eukaryotic cells organelles, such as mitochondria and chloroplasts.

b) 80s ribosomes: These have the sedimentation coefficient of 80s and the molecular weight of $40x10^6$ Daltons. The 80s ribosomes occur in eukaryotic cells.

The ribosomes of mitochondria and chloroplasts are always smaller than cytoplasmic ribosomes and are comparable to prokaryotic ribosomes in both size and sensitivity to antibiotics.

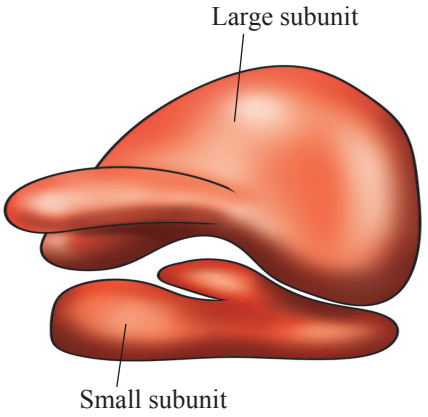


Figure 1.13 Structure of ribosome

Functions of ribosomes

a) Ribosomes are sites of protein synthesis; they provide surface area or space for polypeptide chain construction and enzymes for the synthesis of peptide bonds between amino acid monomers. Hence, they are known as protein factories. The ribosomes are adapted for protein synthesis, as they have ribosomal RNA (rRNA) which provides attachment points for both messenger RNA (mRNA) and transfer RNA (tRNA).

b) Ribosomes have receptor sites on the small sub-unit where mRNA binds itself and they are able to "read" and "translate" the message contained in the mRNA codes.

c) They have enzymes that catalyse the synthesis of peptide bonds.

Lysosomes

Lysosomes are membrane-enclosed organelles that contain an array of enzymes capable of breaking down all types of biological polymers proteins, nucleic acids, carbohydrates, and lipids. The word lysosomes come from the two words *lyso* means 'digestive' and *soma* means 'body.' They are also referred to as suicide bags since they undergo self-destruction, hence the digestion of the entire cell (autolysis). They mostly occur in animal cells and few or rare in plant cells. Lysosomes are not present in bacteria and mature erythrocytes, while a few of them occur in muscle cells. Leucocytes, especially granulocytes, are particularly rich sources of lysosomes. In addition, they are numerous in the epithelial cells of lungs and uterus.

Structure of lysosomes

Lysosomes are round, with vacuolar structure which remains filled with dense material and bounded by a unit membrane. They consist of digestive enzymes, which are synthesized in the ribosomes of the rough endoplasmic reticulum. The enzymes, which always have acidic pH, are transported to the Golgi apparatus for modification. The Golgi apparatus in the cytoplasm concentrates and packs the modified enzymes in the Golgi vesicles, which pinch off as lysosomes. Their shape and density vary greatly from cell to cell and time to time.

Functions of lysosomes

The main functions of lysosome include heterophagy, autophagy and autolysis.

Heterophagy

This is a process whereby lysosomes perform the intercellular digestion of materials that are gathered from outside the cell by endocytosis, which are pinocytosis (taking in liquid materials) and phagocytosis (taking in solid materials). The endocytotically ingested food material is collected in a membrane bounded vesicle called heterophagosomes (pinosomes or phagosomes) and eventually fuse with lysosomes to form phagolysomes in which the engulfed material is digested. Example when bacteria are ingested by phagocytosis, the ingested bacteria are packed in a phagocytic vesicle (phagosomes).This vesicle fuses with a primary lysosome, forming a secondary lysosome. Thereafter, enzymes of the lysosome digest the bacterial macromolecules.

Autophagy

Autophagy allows the orderly degradation and recycling of cellular components. This process occurs when cytoplasmic components become enclosed in a double membrane (phagophore) to form a compartment known as autophagosome for degradation (Figure 1.14). This is the regulated mechanism of the cell that disintegrates unnecessary or dysfunctional components. Autophagy starts with the formation of a phagophore from the membrane; this expands and engulfs the molecules or "cargo" for degradation. The cargo can include redundant organelles or any other chemical aggregates and once engulfed, they are contained within the autophagosome (autophagic vacuole). The latter can then fuse with lysosomes, which result in the release of lysosomal acid enzymes to degrade the contents of the autophagosome. The products of the degradation include amino acids, among other molecules and all of them are released back into the cytoplasm and re-used in metabolism as well as in building macromolecules.

Autolysis

Autolysis is more commonly known as self-digestion, which refers to the destruction of a cell through the action of its own enzymes. Lysosomes break down to release its contents (enzymes) which digest various organelles and finally the entire cell in certain pathological conditions. This process is known as autolysis or self-destruction of the cell.

Exocytosis or extracellular digestion

Exocytosis is the process responsible for breaking down damaged cellular components and some unwanted proteins which are expelled out of the cell. One of the causes of aging is that, in long-lived cells the types of metabolic waste that cannot be broken down accumulates and lysosomes may release them outside the cell by exocytosis. For example; the enzymes of lysosome are released during the replacement of cartilage by bone during development. Also lysosomes of certain cells such as spermatozoa discharge their enzymes outside the cell during fertilization process.

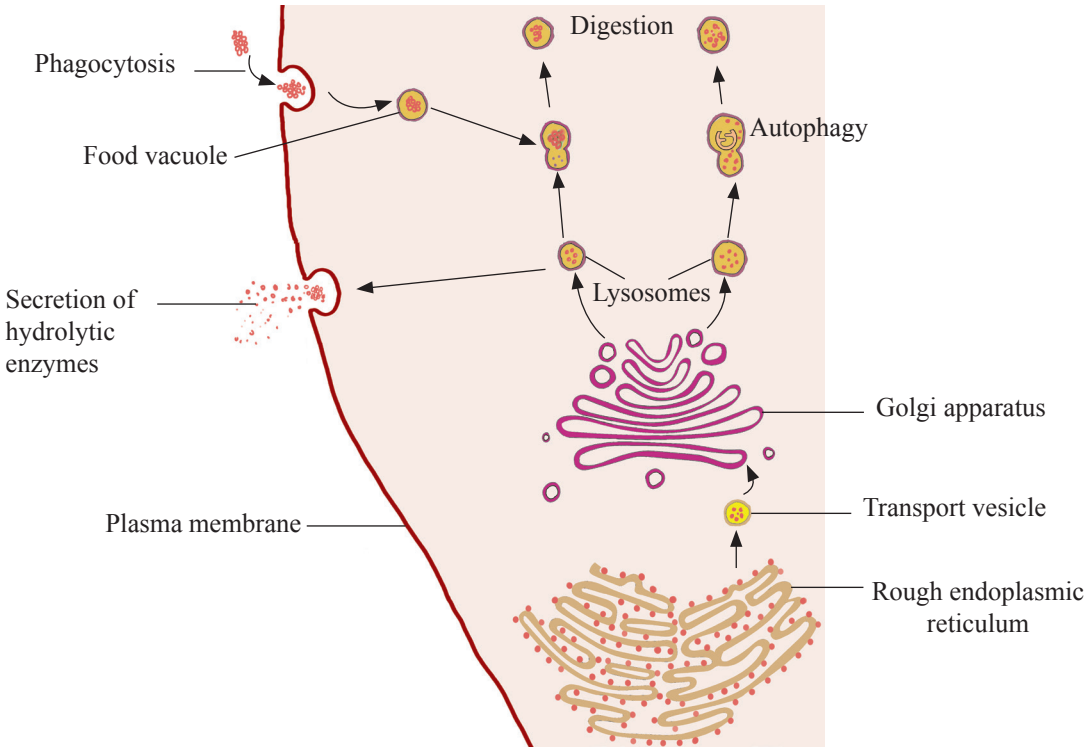


Figure 1.14 Lysosomal functions

Lysosomes are adapted to their functions due to the presence of hydrolytic enzymes which catalyse degradation of unwanted cellular substances. In addition, lysosomes have the membranes that isolate hydrolytic enzymes from the rest of the cytoplasm. This prevents unnecessary autolysis.

Exercise 1.8

1. Why are lysosomes said to be suicide bags?
2. Describe the structure and functions of lysosomes.
3. Giving reasons, mention the parts of your body which are expected to have large number of lysosomes.

Microbodies

Microbodies are small, spherical organelles bounded by a single phospholipid bilayer membrane which contain a matrix of intracellular materials such as catalase (peroxidase) enzyme and other proteins (Figure1.15). They are present in almost all eukaryotic cells and are mostly seen near the ER, and sometimes near mitochondria and plastids. They can be distinguished from other cell organelles by their contents. Microbodies include peroxisomes, glyoxysomes, and glycosomes. Peroxisomes are particularly predominant in the liver and kidney cells of vertebrates, while in plants they are found mostly in plant cells where photorespiration occurs. Glyoxosomes are specialized microbodies found in plants, particularly in fat storage tissues of germinating seeds and in filamentous

fungi. Glycosomes are microbodies which contain glycolytic enzymes in its matrix, and they are believed to have evolved from the peroxisomes. They are found in few species of protozoa such as *Trypanosoma*.

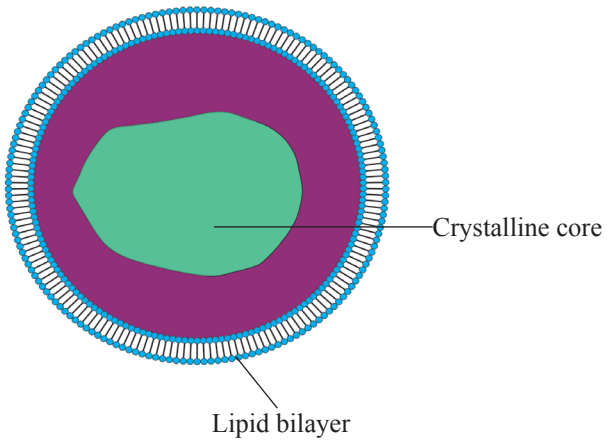


Figure 1.15 Structure of microbody

Functions of microbodies

a) Microbodies such as peroxisomes found in plant and animal cells are involved in the breakdown of poisonous hydrogen peroxide to water and oxygen in the presence of peroxidase enzyme.

$$2H_2O_2 \xrightarrow{\text{Peroxidase}} 2H_2O + O_2$$

b) The peroxisomes contain enzyme glycolic acid oxidase that oxidises glycolic acid, a product of photosynthesis, to glyoxylic acid, by the process called photorespiration.

c) In plants, there are special microbody called glyoxysomes. These are the centre for the glyoxylate cycle, which involves conversion of fats into carbohydrate, especially in germinating seeds.

d) Microbodies also help in conversion of stored lipid in germination oil seeds and liver cells into glucose in the process called gluconeogenesis.

Golgi apparatus

The name of this organelle was derived from its founder, Camillo Golgi, in 1898. He identified it in the nerve cells of the owl and cat. This happened long before the discovery of the endoplasmic reticulum. Golgi apparati are involved in important cellular functions, such as biosynthesis of polysaccharides, packaging of cellular synthetic products, production of exocytotic vesicles, and differentiation of cellular membranes. It occurs in all cells, except in the prokaryotic cells and in cells of certain eukaryotes, such as fungi and bryophytes. It also does not occur in cells of mature sieve tubes of plants, spermatozoa, and in red blood cells.

Structure of the Golgi bodies

It is disc-shaped; consisting of central, flattened, plate-like, compartments or cisternae (Figure 1.16). It is a modified smooth endoplasmic reticulum. The Golgi apparatus is associated with small, spherical sac-like structures called Golgi vesicles. These contain various secretions such as hormones, mucus or enzymes, and they are future lysosomes.

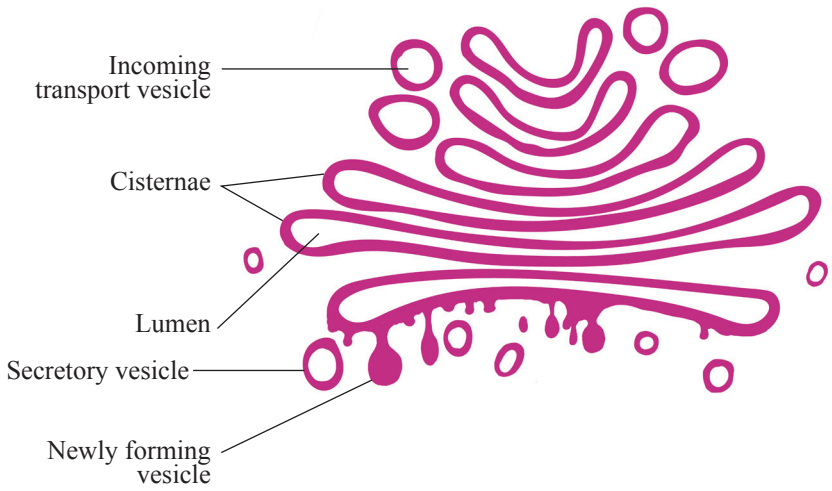


Figure 1.16 Structure of Golgi apparatus

Functions of the Golgi bodies

The functions of Golgi bodies include the following:

a) They form lysosomes.
b) They concentrate and pack secretions, such as enzymes.
c) They are involved in transformation of spermatids into mature spermatozoa.
d) They are involved in formation of primary cell walls in plants.

Cytoskeleton

These are complex network of protein filaments and microtubules which exist in the cytoplasm of eukaryotic cells. It anchors proteins or organelles, such as nucleus to their fixed location. The cytoskeleton consists of microtubules, microfilaments and intermediate filaments (Figure 1.17).

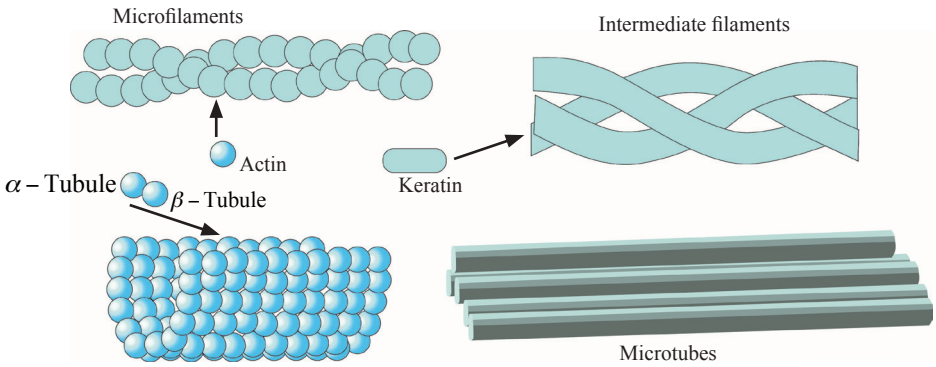


Figure 1.17 Structures of the cytoskeletons

Microtubules

These are tubular structures made up of arranged globular tubulin. They are found in the cytoplasm of animal and plant cells. They occur in cilia, flagella, centrioles, the cortex of meristematic cells, and basal bodies.

Functions of microtubules

a) They determine the shape of the cell.

b) They form a framework along which the plant cell wall is laid down.

c) In cilia and flagella, they help beating of rhythmic movements.

d) They bring about movement of chromosomes during anaphase in nuclear division.

e) Since they are tubular, they transport materials from one part of the cytoplasm to another.

f) They are involved in the movements of other cell organelles such as Golgi vesicles, lysosomes, and mitochondria. For example, the movement of Golgi vesicles towards the center to form cell plate during the formation of a primary cell wall in plant cells is brought about by microtubules.

Microfilaments

These are much narrower than microtubules, being only about 5-7 nm in diameter. They are thread-like structures, arranged in sheets or in bundles beneath the cell surface membrane. They are chemically composed of a large amount of actin, hence their name actin filaments. Actin filaments, usually in association with myosin, bring about many types of cell movements. For example the contractile proteins (actin and myosin) lead to contraction and relaxation of muscles.

Functions of microfilaments

a) They determine the shape of cells; since they offer a cytoskeletal support.

b) The cleavage of animal cells during cytokinesis is brought about by the constriction of a ring of microfilaments after nuclear division.

c) They are responsible for any movement that the cell makes; due to the presence of actin and myosin that influence muscle cells contraction and relaxation.

Intermediate filaments

These structures are found between microtubules and microfilaments. They provide shapes of cells and act as intercellular tendons, preventing excessive stretching of the cells.

Centrioles

A centriole is a cylindrical organelle found in animal cells, algal cells and fungal cells, but not in cells of higher plants. Animal cells contain a pair of centrioles in the cytoplasm which usually lie at right angles to each other close to the nuclear membrane. In cross section, each centriole is seen to contain nine groups of microtubules with three tubules in each group (Figure 1.18). During cell division, the centrioles divide and migrate chromosome in opposite poles of the cell where they act as a focus for spindle formation. Centrioles also produce the basal bodies from which cilia and flagella develop.

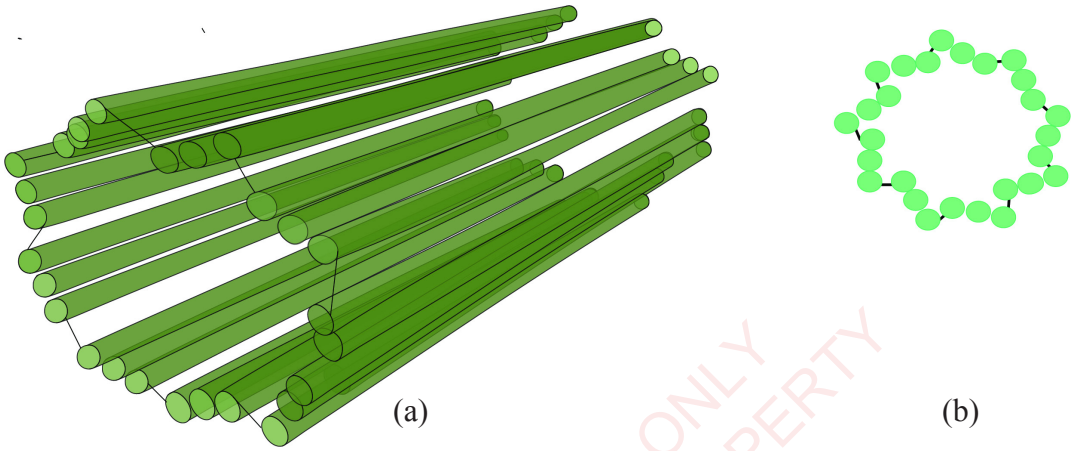


Figure 1.18 Structure of centriole (a) side view and (b) cross section

Exercise 1.9

1. What do you understand by the term cytoskeleton?
2. Explain the functions of microtubules and microfilaments in plant and animal cells.
3. Describe the structure, location and functions of centrioles in animal cell.

Comparison of prokaryotic and eukaryotic cells

Common features which can be found in prokaryotic and eukaryotic cells are as follows:

a) Both have cell membranes that separate the cell's interior from its surrounding environment.
b) Both have a cytoplasm that consists of a jelly-like region within the cell in which other cellular components are floating.
c) Both have ribosome particles that synthesize proteins, and the genetic material of the cell.

The prokaryotic and eukaryotic cells also differ in many aspects as elaborated in the Table 1.1.

Table 1.1 Differences between prokaryotic and eukaryotic cells

Criteria/ Feature	Prokaryotic cells	Eukaryotic cells
Cell type	Mainly unicellular (some cyanobacteria may be multicellular).	Mainly multicellular (except kingdom Protoctista which have many unicellular organisms).
Nucleus	Have no true nucleus.	Have a true nucleus, bound by a double membrane.
Double membrane bound organelles	Have no double membrane bound organelles.	Have many double membrane bound organelles, such as mitochondria, chloroplasts, and nucleus.
DNA	Have circular DNA.	Have helical or linear DNA.
	Have naked DNA.	Have DNA associated with proteins known as histones and is organised into chromosomes.
Ribosomes	Have small and simple ribosomes (70s ribosomes).	Have larger and more complex ribosomes (80s ribosomes).
Cytoplasm	Have only one type of organelles, that is, the ribosomes.	Filled with a large and complex collection of organelles, many of them enclosed in their own membranes.
Cell size	Small in size	Relatively large in size.
Functional compartments	Have only one membrane (the plasma membrane) enclosing all of the cell's internal contents.	Have many different functional compartments divided by membranes.
Cell wall	Mureinic cell wall.	Cellulose or chitinous cell wall.
Cilia and flagella	Do not arise from basal bodies and lack micro-tubules.	Arise from basal bodies and have 9+2 arrangement of microtubules.
Cell division	Involves binary fission or budding.	Involves mitosis, meiosis or both.
Reproduction	No meiosis. Transfer of DNA is done by conjugation only.	Involves meiosis during gamete formation.

1.3.3 Cell differentiation

Cellular differentiation is the process of cell transformation from one form to another. It leads to the development of specialised types of cells for carrying out specific functions. This process involves biochemical and structural changes. The differentiated cells become more specialised than the undifferentiated ones.

In most cases differentiation occurs during the development of a multicellular organism, as it changes from a simple zygote to a complex system of cell types or tissues. The process continues to adulthood; as adult stem cells divide and create fully differentiated daughter cells during tissue repair. Differentiated cells change in size, shape, membrane potential, metabolic activity, and responsiveness to signals. Cell differentiation leads to cell specialisation, which in turn leads to division of labour that improves efficiency of the organisms. Examples of specialised cells in animals are sex cells, nerve cells, red blood cells, and epithelial cells; and in plants are xylem, phloem, root hair, and parenchyma cells. Figure 1.19 shows root hair cell as an example of specialised plant cell.

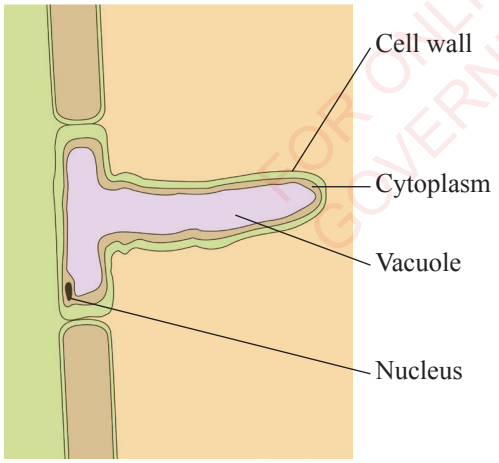


Figure 1.19 Root hair cell

Significance of cell differentiation

Cell differentiation has the following significance:

a) It modifies cells to suit their functions more efficiently. This means that, during differentiation the cell becomes equipped with structural and/or chemical changes to enhance its efficient.

Examples include:

i) Spermatozoa are packed with numerous mitochondria and acrosomal enzymes. They also have flagella. All these features facilitate efficient fertilisation of egg cells.

ii) Female gametes (egg cells) have numerous microvilli for absorption of food from follicular cells. They also have a large proportion of cytoplasm which contains food reserve for the developing embryo.

iii) Nerve cells have features like myelin sheath and nodes of Ranvier, which facilitate rapid transmission of impulses. The synaptic vesicles contain neurotransmitters that aid in synaptic transmission of impulses.

iv) The cells in xylem vessels and tracheids are hollow, and have lignified cell walls for efficient carriage of water and dissolved mineral salts.

b) It enables cellular organization, as a way of forming different tissues and organs (organogenesis) through the expression of a specific set of genes within the body to perform more specialized and complex tasks.

c) It forms the basis for embryonic stem cell research, whereby researchers

can identify stem cells, which can be used in the future to deal with the conditions that require transplanting, such as kidney transplanting.

d) It helps in the future treatment of cancer patients by enabling measurement of the cancer progress at cellular level, where the cytopathologists term 'grade' is used as a marker to determine how differentiated cell in a tumor is.

Activity 1.3 Observation of a specialised root hair cell

Materials

Onion roots, surgical blade, iodine solution, petri dish, dropper, light microscope, and microscope slides.

Procedure

a) Take the onion root, and use a surgical blade to cut it transversely into very thin slices.
b) Put a slice on the petri dish, and add one drop of iodine solution using a dropper.
c) Transfer the stained slice to the microscope slide.
d) Observe the stained slice under a light microscope.

Questions

1. What conclusion can you make from what you have observed?
2. What are the features that characterise a specialised onion cell?

Safety precautions

Observe safety precautions when working with sharp objects such as knife and surgical blade.

Exercise 1.10

1. Explain features which are found in both prokaryotic and eukaryotic cells.
2. Using examples, explain the concept of cell differentiation.
3. Explain why cell differentiation is generally referred to as a cellular division of labour.
4. What is the importance of cell differentiation in animals and plants?

1.4 The organic constituents of cells (Biochemistry)

The cells are composed of water, inorganic ions and organic molecules (carbon-containing compounds). Water is the most abundant molecule which constitutes large part of cells, constituting about 70% of the total mass. It also interacts with other constituents in the biochemistry of life. The organic components of the cells include: Carbohydrates, proteins, lipids, enzymes, nucleic acids and regulatory substances such as hormones and vitamins.

1.4.1 Carbohydrates

Carbohydrates are among of the fundamental classes of macromolecules found in living organisms. These are molecules which contain the carbonyl compound (aldehyde and ketone derivatives). They are primary products of photosynthesis, and energy providing substrates for various organisms including mammals. Carbohydrates contain three elements, namely carbon, hydrogen, and oxygen, in which hydrogen and oxygen are in the ratio of 2:1 (two hydrogen atom

and one oxygen atom). This ratio or proportion of hydrogen to carbon is the same as in water, hence the name hydrate of carbon. The general empirical formula for carbohydrates is $C_x (H_2O)_y$ where by x and y are variables.

Properties of carbohydrates

They are either simple sugars or compound sugars. The latter are formed by condensation of the former. For example; starch is formed by condensation of several glucose units. They have one hydrated carbon (CH_2O), hence the name carbohydrates. The ratio of hydrogen to oxygen in a carbohydrate molecule is always 2:1. They are derivatives of polyhydroxyl alcohols and can be polyhydroxy aldehydes with an aldehyde group H-C=O, examples are glyceraldehyde, ribose, glucose, and galactose sugars. They can also be polyhydroxy ketones with a ketone group (C=O), examples are dihydroxyacetone, ribulose, and fructose sugars. Carbohydrates can be oxidised to yield energy. For example, the oxidation of glucose during respiration.

$$C_6H_{12}O_6 + 6O_6 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

Aldoses and ketoses are reducing compounds; they have a tendency of reducing Copper (II) in Benedict's solution into Copper (I), which precipitates as a red solid substance of Copper (I) oxide.

Classes of carbohydrates

Carbohydrate can be classified according to the number of basic sugars or saccharide units present in a molecule. These classes include the following:

a) Monosaccharides
b) Disaccharides
c) Polysaccharides

Table 1.2 Major types of carbohydrates and their sources

Type	Examples	Sources
Monosaccharides	Fructose	Sweet fruits and honey.
	Glucose	Fruits, such as grapes, coconut water, and sweet potatoes.
	Galactose	Milk and dairy product.
Disaccharides	Sucrose	Sugar cane and carrots.
	Lactose	Milk.
	Maltose	Malt, such as radicles of germinating cereals.
Polysaccharides	Starch	Yam, irish potatoes, sweet potatoes, and green banana.
	Cellulose	Cell walls of various plant cells.
	Chitin	Cell walls of fungal hyphae, and the exoskeleton of arthropods such as insects, crabs, and prawns.

Monosaccharides (Single sugars)

These are the simplest carbohydrates, having only one sugar or saccharide molecule, which cannot be hydrolysed into small molecules. They are classified according to two different characteristics; the placement of its carbonyl group and the number of carbon atoms it contains. As for the first characteristic, if the carbonyl group is an aldehyde, the monosaccharide is an aldose and if the carbonyl group is a ketone, the monosaccharide is a ketose. Monosaccharide are further classified according to the number of carbon atoms they contain, therefore, monosaccharides with three carbon atoms are called trioses; those with four carbon atoms are called tetroses; those with five carbon atoms are called pentoses; and those with six carbon atoms are called hexoses. These two systems of classification of monosaccharides are often combined. For example, glyceraldehyde an aldotriose (a three-carbon aldehyde), ribose is an aldopentose (a five-carbon aldehyde), glucose is an aldohexose (a six-carbon aldehyde), dihydroxyacetone is a ketotriose (a three-carbon ketone), ribulose is a ketopentose (a five-carbon ketone) and fructose is a ketohexose (a six-carbon ketone).

Trioses These are the smallest molecules of monosaccharides which contain three carbon atoms in their molecules. Examples are glyceraldehyde and dihydroxyacetone. Their empirical formula is $C_3H_6O_3$.

Tetroses They are monosaccharides containing four carbon atoms such as erythrose and threose. Their empirical formula is $C_4H_8O_4$.

Pentoses They contain five carbon atoms in their molecules, examples are ribose, deoxyribose, ribulose and arabinose. Their empirical formula is $C_5H_{10}O_5$.

Hexoses These are monosaccharides containing six carbon atoms in their molecules, such as glucose, fructose, and galactose. Their empirical formula is $C_6H_{12}O_6$. They are the most common monosaccharides.

Heptoses They contain seven carbon atoms in their molecules. Their empirical formula is $C_7H_{14}O_7$.

Properties of monosaccharides

Most of the monosaccharides have a sweet taste. They exist in a crystalline solid form at room temperature and are extremely soluble in water; despite their high molecular weights. The presence of large number of OH groups makes the monosaccharides much more water soluble than most other molecules of similar molecular weight. Moreover, all monosaccharides are reducing sugars; as they have free aldehyde or ketone group. They reduce mild oxidizing agents, such as Tollens', Fehling or Benedict's reagents.

Open chain and ring forms of pentose and hexose sugars

Pentose and hexose sugars can exist in both open chains (straight structures) and ring structures. Example furanose or furan ring has five membered ring, and pyranose or

pyran ring has six membered ring structures. These aromatic ring forms are the most stable and used to form disaccharides and polysaccharides. The ring form occurs in aqueous solution and can form two isomers which are either alpha (α) or beta (β) isomers. The α form is when the hydroxyl (OH) group on carbon atom number 1 projects below the ring while β form is when the OH group on carbon atom number 1projects above the ring. Pentose sugars may form the five membered ring when their carbon atom number 1 joins with the oxygen atom of carbon number 4, an example is as shown in ribose and deoxyribose sugars (Figure 1.20 a and b). The only difference that exists between ribose and deoxyribose sugar is that deoxyribose sugar lacks oxygen in carbon number 2. Hexoses can form both six and five membered ring. For example glucose can exist in two isomers of six membered rings (α- glucose or β-glucose). The formation of ring form is when the oxygen atom of carbon number 5 joins to the carbon number 1 bearing the aldehyde and transfer its hydrogen to it and break the bond to form the OH either above or below the ring. The oxygen is part of the ring and carbon number 6 sticks up out of the ring. The same process occurs in galactose. The only difference between galactose and glucose is the different orientation of their hydroxyl group in carbon number 4 (Figure 1.20 c and d). In fructose, the carbonyl group is in carbon number 2, so the ring is formed by the oxygen atom of carbon number 5 joining with carbon number 2, leading to the formation of furan ring. When the OH in carbon atom number 1 is projected below the ring, it becomes α-fructose while when OH in carbon atom number 2 is projected above the ring is β-fructose (Figure 1.20 e). Fructose can also form the pyronose as in glucose.

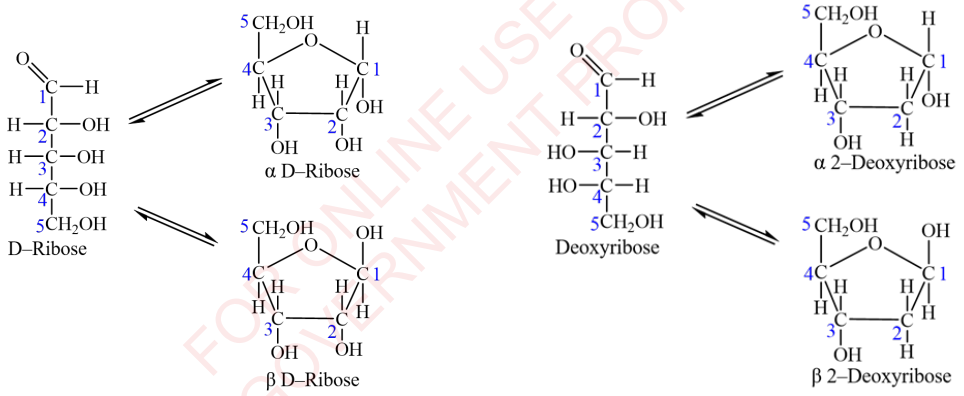


Figure 1.20 Open chain and ring form of (a) ribose and (b) deoxyribose

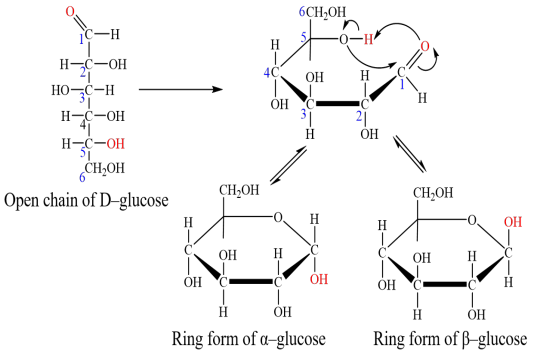


Figure 1.20 (c) Open chain and ring structures of glucose

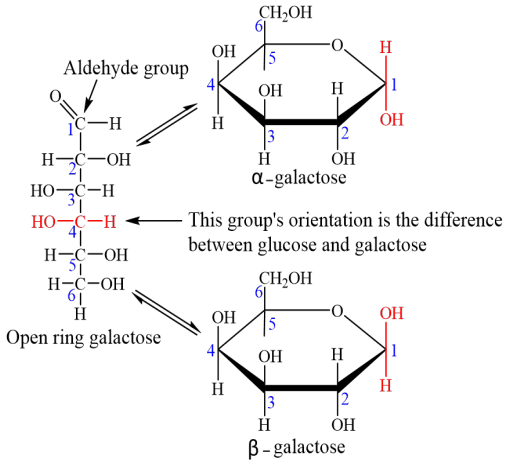


Figure 1.20 (d) Open and ring form of galactose

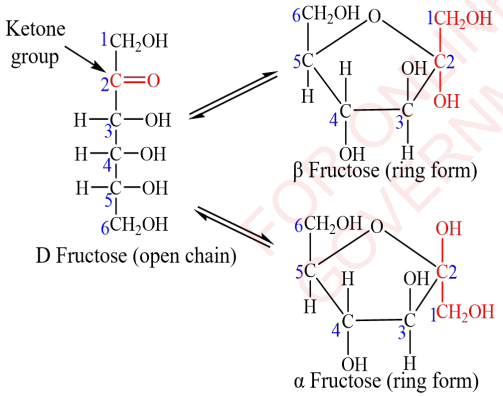


Figure 1.20 (e) Open chain and ring form of fructose

Disaccharides (double sugars)

They are formed through condensation of two monosaccharides; examples include sucrose, maltose, and lactose. They are composed of two monosaccharide units bound together by a covalent bond known as a glycosidic bond. They are formed via dehydration (condensation) reaction resulting in the loss of a hydrogen atom from one monosaccharide and a hydroxyl group from the other. The formula of disaccharides is $C_{12}H_{22}O_{11}$. Although there are numerous kinds of disaccharides, a handful of disaccharides are particularly notable. Sucrose is the most abundant disaccharide, and the main form in which carbohydrates are transported in plants. It is composed of one glucose molecule and one fructose molecule. Lactose, a disaccharide composed of one galactose molecule and one glucose molecule, occurs naturally in mammalian milk. Other notable disaccharides include maltose which is made up of two glucose molecules linked by 1, 4 –glycosidic bond.

Properties of disaccharides

Disaccharides are composed of two molecules of monosaccharides linked to each other by glycosidic bond. Like monosaccharides, disaccharides are sweet in taste and crystalline water soluble compound. All disaccharides cannot pass through the plasma membrane of the cell, since there is no carrier enzyme that can carry disaccharides to move across the plasma membrane. Among disaccharides, maltose and lactose are reducing sugars, while sucrose is a non-reducing sugar.

Maltose (malt sugar)

Maltose is a double sugar which occurs naturally in roots and radicles of germinating cereals, such as maize, sorghum and finger

millet. Artificially, it is made up by chemical combination of two α-glucose units. During this combination -OH group at carbons 1 and 4 of the two glucose residues, are involved in formation of oxygen covalent bond called glycosidic bond. Since it is formed between carbons 1 and 4, then it is termed a 1, 4-glycosidic bond. This process involves condensation, therefore, a molecule of water is lost (Figure 1.21). Maltose is a reducing sugar since it has a free aldehyde group in its molecule. In one of the glucose units, the aldehyde at carbon 1 has been used in the formation of the bond, while in the second glucose unit, the aldehyde at carbon 1 remained intact, since the carbon involved in the formation of the bond is that at position 4.

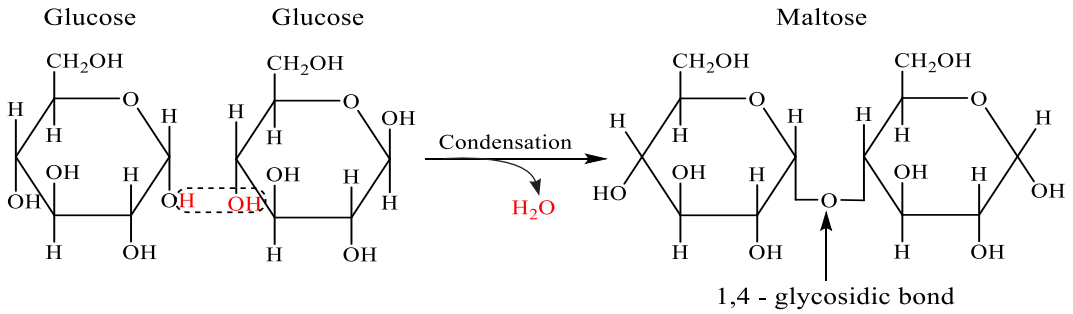


Figure 1.21 Chemical combination of two a-glucose units to form maltose

Sucrose (cane sugar)

This is a double sugar that naturally occurs in stems of sugar cane plants. It is made up by chemical combination of glucose (an aldose sugar) and fructose (a ketose sugar). During the reaction, the –OH group at carbon 1 of glucose and that at carbon 2 of fructose contribute to the formation of the 1,2-glycosidic bond. The reaction is also condensation; therefore, a molecule of water is lost (Figure 1.22). Sucrose is a non-reducing sugar because it lacks any active reducing group. The aldehyde group at carbon 1 of glucose and ketone group at carbon 2 of fructose have their –OH group contributing to the formation of the glycosidic bond.

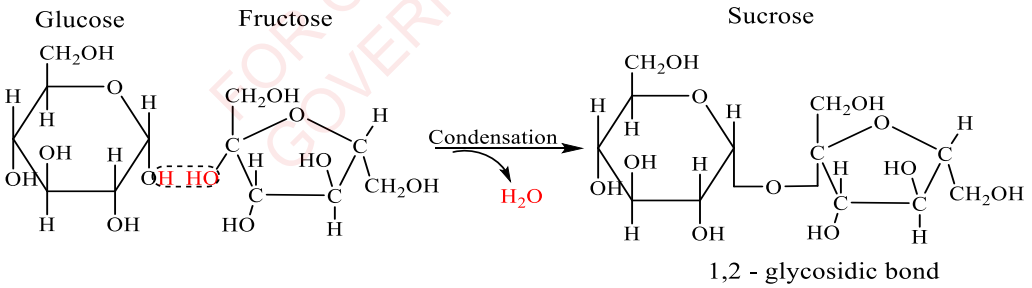


Figure 1.22 Chemical combination between glucose and fructose to form sucrose

Lactose (milk sugar)

This is found exclusively in the milk of mammals and in milk products. Lactose is the only carbohydrate of milk which is synthesized by mammary gland during lactation. It is derived from the condensation of galactose and glucose linked by 1, 4 - glycosidic bond (Figure 1.23).

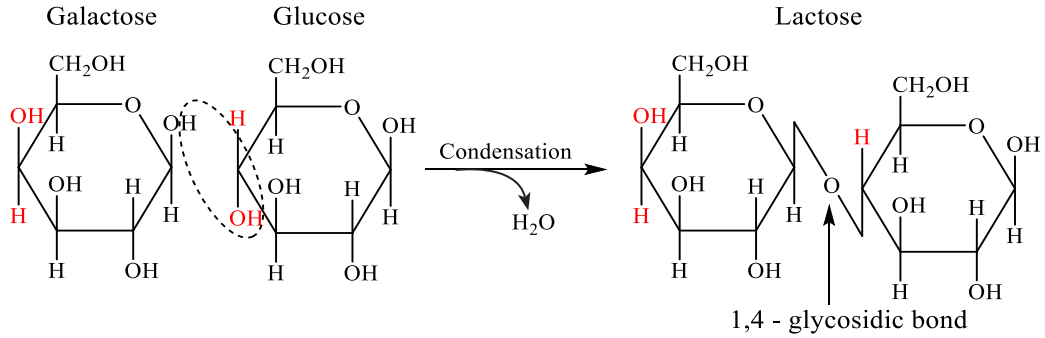


Figure 1.23 Chemical combination between galactose and glucose to form lactose

Polysaccharides (multi-sugars)

Polysaccharides are polymer carbohydrate molecules, composed of long chains of monosaccharide units bound together by glycosidic bonds. On hydrolysis, they give their constituent monosaccharides. They range in structure, from linear to highly branched molecules, examples include storage polysaccharides such as starch and glycogen as well as structural polysaccharides such as cellulose and chitin. Starch is the main storage of polysaccharides in plants. It is made up of two polymers, amylose and amylopectin while in animals and fungi, glycogen is the main storage form of polysaccharides. In plants, cellulose is a structural constituent of their cell walls while in fungi and most arthropods, chitin is the structural constituent of the cell wall and exoskeleton respectively.

Properties of polysaccharides

Polysaccharides are complex carbohydrate polymers, consisting of several monosaccharides, linked together by glycosidic bonds. They are large molecules which are often insoluble in water and exist in non-crystal form.

Starch

Starch is a polymer of hexose sugar (α glucose) that can be extracted as a white powder. It is a major storage carbohydrate of plants, and it is a product of photosynthesis. Chemically, starch is a polymer of repeated α-glucose units that are bonded together by glycosidic bonds. This polysaccharide is a mixture of two substances; amylose and amylopectin. Amylose unit is a linear, helical chain which consists of around 500 to 20,000 monosaccharides connected by α (1-4) glycosidic bonds between the glucose units. Amylopectin differs from amylose in being highly branched, and has short side chains of about 30 glucose units linked with α (1-6) glycosidic bonds in addition to 1,4-glycosidic bonds (Figure 1.24). Amylopectin molecules may contain up to two million glucose units.

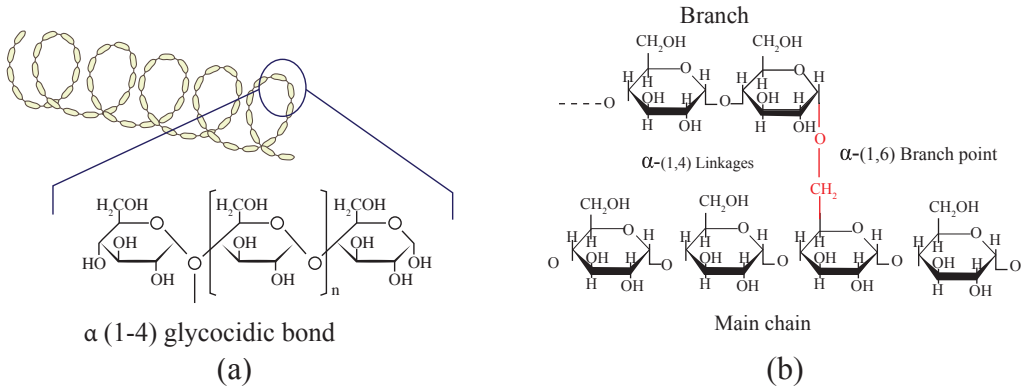


Figure 1.24 Structures of (a) amylose and (b) amylopectin

Glycogen

Glycogen is the form in which polysaccharide is stored in animals and fungi. It is often called an animal starch, and it is stored mainly in liver and skeletal muscles. Like starch, it is made up of α-glucose molecules and exists as granules. Structurally, it resembles amylopectin, except that it is more branched, and its chains are shorter (Figure 1.25). The glucose chains are organized globularly like branches of a tree. They originate from a pair of molecules of glycogen in a protein which acts as a primer at the core of the structure. Glycogen can be converted back into glucose when energy is needed through the process called glycogenolysis. Glycogen is easily converted back to glucose in order to provide energy for body activities. When glucose cannot be stored as glycogen or used immediately for relese of energy, it is converted into fat.

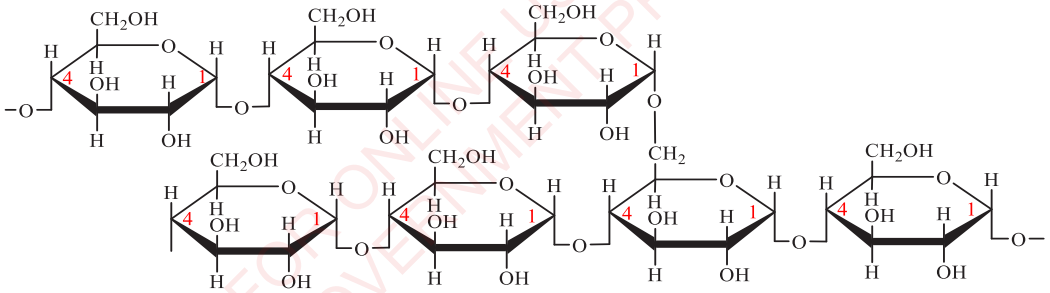


Figure 1.25 Structure of glycogen molecule

Cellulose

Cellulose is an important structural polysaccharide of plants, which largely constitutes the chemistry of the cell wall. It is chemically composed of several thousands of β-glucose units, joined together by 1, 4-glycosidic bonds, to form long, unbranched chains. Many chains run parallel to each other and have cross linkages between them (Figure 1.26). These help to

give cellulose its considerable stability to make it a valuable structural material. It is the major component of the plant cell walls, where it plays structural role.

Cellulose's structural strength has made it a valuable raw material in manufacturing various industrial products, such as cotton, which is a pure form of cellulose. It is also used for manufacturing of fabrics. Rayon, a product of cellulose extract is used in manufacturing of industrial belts, tyre cods and clothing. Cellulose derivatives have various uses, for example; cellophane is used in packaging, and celluloid is used for manufacturing of photographic film. Other cellulose products include paper and explosives.

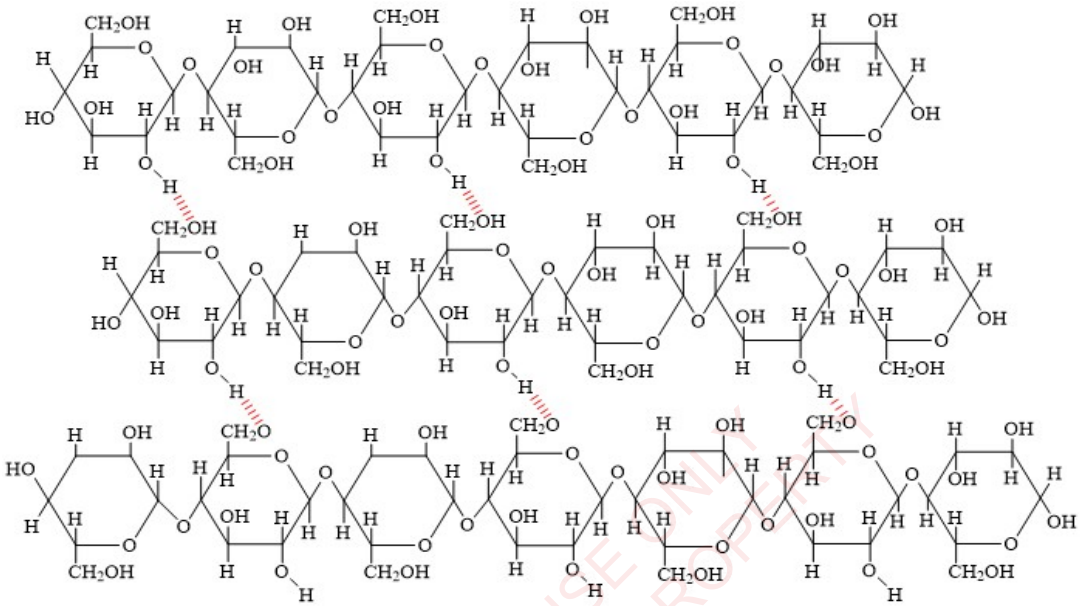


Figure 1.26 Structure of cellulose

Chitin

Chitin is an extracellular structural polysaccharide found in large quantities in the body covering cuticle of insects and exoskeletons of crustaceans. Chitin is also found in smaller amounts in sponges, molluscs, annelids and cell walls of fungi. Also, been identified in the cell walls of some green algae. Its structure and chemistry are similar to those of cellulose. Chitin, like cellulose, has its repeating units joined in β (1,4) linkages. However, the two differ in that, the hydroxyl group (-OH) of chitin at carbon atom number two (C-2), is replaced by $–NH.CO.CH_3$ (acetyl-amino) group. It is thus a result of an amino sugar, glucose amine, combining with an acetyl group ($CH\ CO^-$). Chitin, is therefore a polymer of acetyl, glucose and amine (Figure 1.27).

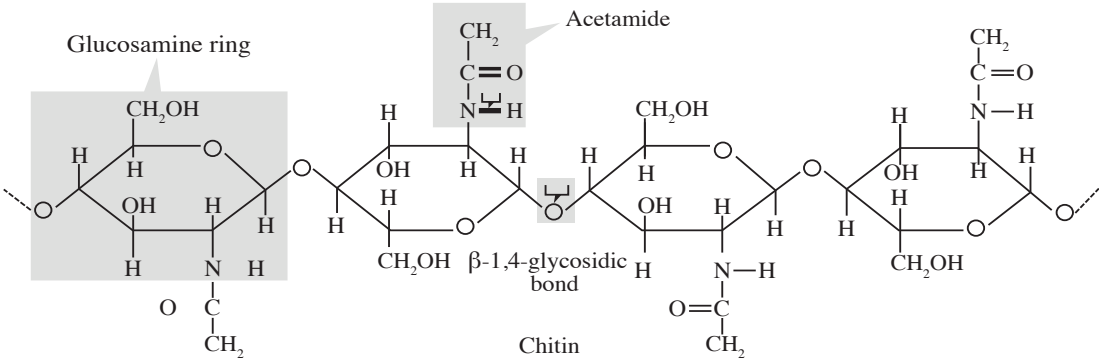


Figure 1.27 Structure of chitin

Chitin has also been proven to be useful for several medical and industrial purposes.Chitin is used as a flocculating agent for waste water, wound-healing agent, a thickener and stabilizer for foods and pharmaceuticals. Also, it used as a binder for dyes, fabrics, and adhesives, and a sizing and strengthening agent for paper. In butterfly wing scales, chitin is often organized into stacks of nano-layers or nano-sticks made of chitin nanocrystals that produce various iridescent colours by thin-film interference.

Biochemical test for carbohydrates

Carbohydrates are carbon compound that have polyhydroxy aldehydes and polyhydroxy ketones, with reducing properties. Carbohydrates may be present as isolated molecules or they may be physically associated or chemically bound to other molecules. The specific test for a particular type of carbohydrate is based on the presence of specific component of carbohydrate or the reducing properties resulting from aldehyde or ketone groups.

Different methods can be used to test for the presence of starch, reducing sugars and non-reducing sugars (Table 1.3).

a) Biochemical test for starch

The presence of starch in biological materials can be tested by using Iodine solution. The use of iodine to test the presence of starch is one of common experiments. A solution of iodine (I_2) and potassium iodide (KI) in water has a light orange-brown colour. If is added to a sample that contains starch, the color changes to a dark blue (or blue black). In the absence of starch, the orange-brown colour of the aqueous solution remains.

The basis of the test

The Iodine bound inside the helical structure of the amylose forms a dark blue colour. The reaction is due to the formation of polyiodide chains (complex) from the reaction of starch and iodine. The amylose in starch forms helices where iodine molecules are assembled, forming a dark blue colour (Figure 1. 28).

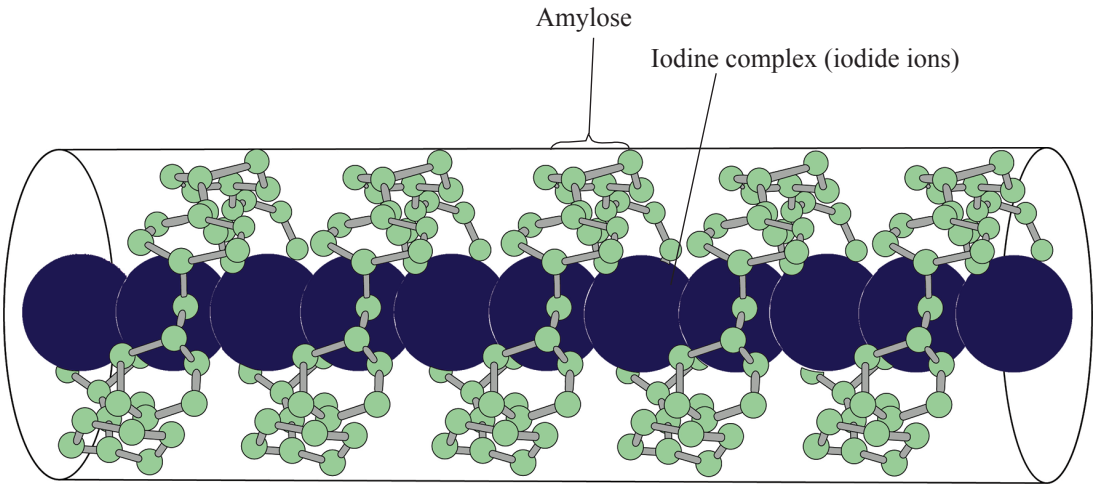


Figure 1.28 A helical structure of amylose bound the iodine molecule

b) Biochemical test for reducing sugars

All monosaccharides and some disaccharides, including maltose and lactose (with exception of sucrose), are reducing sugars; as one of the two units may have an open-chain form with an aldehyde group. This means that they carry out a type of chemical reaction known as reduction. The characteristic property of reducing sugars is that, in aqueous medium, they generate one or more compounds containing an aldehyde group. An aldehyde can be the source of electrons that reduces ions. The oxidizing agent must be capable of oxidizing aldehydes, but not alcohols. Such oxidising agents include Benedict's solution ($CuSO_4$/citrate), Fehling's reagents ($CuSO_4$/tatrate), and Tollen's reagent $[2[Ag(NH_3)_2]^+]$. However, sucrose, in which the anomeric carbons of the two units are linked together, are non-reducing disaccharides since neither of the rings is capable of opening. Such disaccharides do not have a free reducing group and are therefore non-reducing sugars.

The common test for reducing sugar is Benedict's test. Fehling's reagent is not commonly used because it is corrosive and toxic**.** In this test, Benedict's solution makes use of the ability of these sugars to reduce copper (II) into copper (I). The test involves the use of an alkaline solution of Copper (II) Sulphate ($CuSO_4$) which is reduced to insoluble Copper (I) oxide (Cu_2O). In the absence of reducing sugar, the blue colour of the Benedict's solution remains.

The basis of the test

Benedict's solution contains copper sulphate. Reducing sugars reduce soluble blue copper sulphate; containing copper (II) ions (Cu^{2+}) to insoluble red-brown copper oxide containing copper (1).

$$Cu^{2+} + e^- \longrightarrow Cu^+$$

Blue solution → Brick red ppt

c) Biochemical test for non-reducing sugar

A non-reducing sugar is a carbohydrate that is not oxidized by a weak oxidizing agent in basic aqueous solution.

Table 1.3 Test for starch, reducing sugar and non-reducing sugar

Food sample to be tested	Procedure	Observation	Inference
Starch	**Iodine test** Place 2 ml (cm^3) of 1% starch solution in a clean and dry test tube. Add 3 drops of iodine solution (No heating is required). Alternatively, add the Iodine solution to the solid form of starch.	Blue-black colouration is observed.	Starch present.
Reducing sugar	**Benedict's test** Place 2 ml of a solution containing reducing sugar solution in a clean and dry test tube. Add 2 ml of Benedict's solution, and heat gently to boil.	The initial blue colouration of the mixture turns green, then yellowish to orange and may finally form a brick- red precipitates.	Reducing sugar present.
Non-reducing sugar	Place 2 ml of non- reducing sugar (such as sucrose) solution in a clean and dry test-tube. Add 1ml dilute hydrochloric acid, heat gently, then allow to cool. Carefully, neutralize with 1 ml of sodium hydroxide solution. Add 2 ml of Benedict's solution and heat to boil.	The initial blue colouration of the mixture turns green, then yellowish to orange and may finally form a brick-red precipitates.	Non – reducing sugar present.

In basic aqueous medium, non-reducing sugars do not generate any compounds containing an aldehyde group. Due to that, it cannot donate electrons to other molecules; hence, cannot act as a reducing agent. Sucrose is the most common non-reducing sugar. The linkage between the glucose and fructose units in sucrose, which involves aldehyde and ketone groups, is responsible for the inability of sucrose to act as a reducing sugar. A non-reducing sugar does not reduce copper (II) sulphate; therefore, there is no direct test for it. However, if it is first hydrolysed to its constituent monosaccharides, it will then give a positive Benedict's test results.

The basis of the test

A non-reducing sugar (sucrose) can be hydrolysed by heating with dilute hydrochloric acid to give glucose and fructose, both of which are reducing sugars. The solution is neutralized with dilute sodium hydroxide or potassium hydroxide so as to give the reducing sugar results with the Benedict's test on heat.

Activity 1.4 Biochemical test for carbohydrates

Materials

Sweet potatoes, coconut seed, apparati (test tubes, test tube racks, test tube holder and brush, beaker, scalpel or surgical blade, measuring cylinder, droppers, mortar and pestle), reagents (Benedict's solution, iodine solution, dilute hydrochloric acid, dilute sodium hydroxide solution, and distilled water), and a source of heat.

Procedure

a) Prepare two solutions, one from sweet potatoes and another one from coconut pulp.

b) Carry out biochemical test using the given reagents and apparati to investigate food substances present in each of the solutions.

Question

State roles of each food substance found in the tested solutions.

Functions of carbohydrates

a) Monosaccharides, such as hexoses are used to form disaccharides and polysaccharides which are other types/ forms of carbohydrates.

b) Carbohydrates are the chief energy sources in living organisms because they are oxidised to give energy. For example, glucose is the most common respiratory substrate which when completely oxidised, yields about 38 ATP.

c) Trioses such as glyceraldehyde and dihydroxyacetone are used as intermediates in respiration, photosynthesis and other carbohydrate metabolic processes. During respiration (during glycolysis), six carbon sugar splits to form dihydroxyacetone phosphate and phosphoglyceraldehyde which enters the cycle, whereas during dark reaction of photosynthesis the formed phosphoglyceraldehyde becomes a source of lipids and proteins.

d) They are the sources of other food substances, such as a triose sugar in plants.

e) Pentose sugar, such as ribose and deoxyribose sugars used in the synthesis of nucleic acids. Ribose is a constituent of Ribonucleic acid (RNA) and deoxyribose is a constituent of Deoxyribonucleic acid (DNA).

f) Ribose sugar is also used in the synthesis of ATP and coenzymes, such as NAD and NADP.

g) Carbohydrate such as ribulose (a five carbon sugar) forms Ribulose biphosphate, which is used as carbon dioxide acceptor during light independent stage of photosynthesis.

h) In association with proteins and phospholipids, they form structural parts of a membrane.

i) They form structural parts of organisms, examples: cellulose in plant cells and chitin in exoskeleton of arthropods.

j) They are important constituents of connective tissues in animals.

k) Cellulose fibres in edible fruits and otherfoods help to prevent constipation in humans.

l) Flower nectar contains sugar, which is important in the process of pollination.

Activity 1.5 Biochemical test for carbohydrates

1. Suppose you have been provided with the following for a practical work:
   a) Solution K containing starch
   b) Benedict's solution
   c) Dilute hydrochloric acid
   d) Sodium hydroxide solution
   e) Rubber bands for stimulating saliva secretion

Questions

1. Show step by step, how you would go about testing for starch.
2. It is advised that, before collecting saliva, one should rinse his or her mouth with clean safe water. What is the significance of this?
3. Comment on the final colour change of the solution.

Exercise 1.11

1. With illustrations, differentiate between monosaccharides and disaccharides.
2. Explain the roles of carbohydrate in the human body.
3. Show how two glucose units are combined to produce maltose. Give details of chemical reactions involved and the bond formed.
4. Can sucrose reduce Copper (II) in Benedict's solution? Give an annotated description of your answer.
5. Show how the structure of α-glucose is maneuvered to produce β-glucose, galactose and fructose.

1.4.2 Lipids

Lipids are made up of carbon, hydrogen, and oxygen in which the content of oxygen is always smaller compared to carbon and hydrogen. Lipids are important constituents of the diet, because they are the source of high energy value. Natural fats and oils are compounds of glycerol and fatty acids. They are esters which are formed as the result of the reaction between organic acids and alcohols.

Formation of lipids

Lipids are esters formed by the reaction between fatty acids and alcohols. In simple lipids such as fats and oils, the alcohol involved in the reaction is glycerol. The formation of lipids is by condensation reaction; therefore, a molecule of water is lost. This forms a covalent bond called ester bond.

Types of lipids

In the year 1943, Bloor proposed the classification of lipids based on their chemical composition as simple lipids, compound lipids, and derived lipids.

a) Simple lipids or homolipids

These are esters of fatty acids and various alcohols. Such lipids include fats and oils (whose alcohol is glycerol) and waxes which contain alcohols higher than glycerol. Fats differ from oils in that they contain fatty acids with saturated hydrocarbon chain. In oils, fatty acids contain unsaturated hydrocarbon chains. At room temperature, oil is liquid, while fat is solid. Fatty acids have a general formula of $CH_3 (CH_2)_n COOH$ where 'n' is a whole number. Stearic acid is a common fatty acid in animals' adipose tissue. The fats and oils are triglycerides, formed by the combination of one trihydroxyl alcohol, (glycerol), and three fatty acid molecules. In this process, three molecules of water are lost and the ester bond is formed (Figure 1.29).

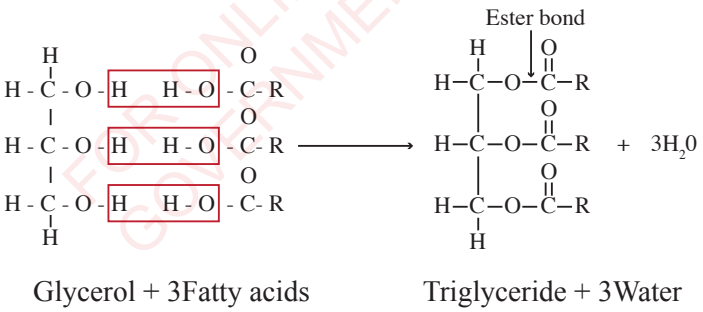


Figure 1.29 Formation of triglyceride

b) Compound lipids or heterolipids

These are esters of fatty acids with alcohols that possess additional groups which may be derived from other acids other than fatty acids. The compound lipids contain fatty acids, alcohols, and other compounds, such as phosphorous, amino-nitrogen and carbohydrates as shown in table (1.4).

Table 1.4 Compound lipids

Phospholipids or phosphatides	These contain a phosphate group. Their glycerol forms ester bond with phosphoric acid and two fatty acids (Figure 1.30). They usually contain one hydrophilic head and two hydrophobic tails. They are called polar lipids and are amphipathic in nature.
Glycolipids	Glycolipids are compound lipids with carbohydrates. These lipids include also certain structurally related compounds comprising of gangliosides, sulpholipids, and sulfatides groups.
Sphingolipids or phosphosphingosides	Sphingolipids occur mostly in the cells of the brain. They do not contain glycerol in their molecules; instead, they contain amine alcohol (sphingosine or sphingol). For instance, the myelin sheath of the nerve fibres contains a lipid known as sphingomyelin, which contains sphingosine and phospholipids in its molecules. Terpenes are mostly found in plants. Examples of terpenes are natural rubber and gern oil.

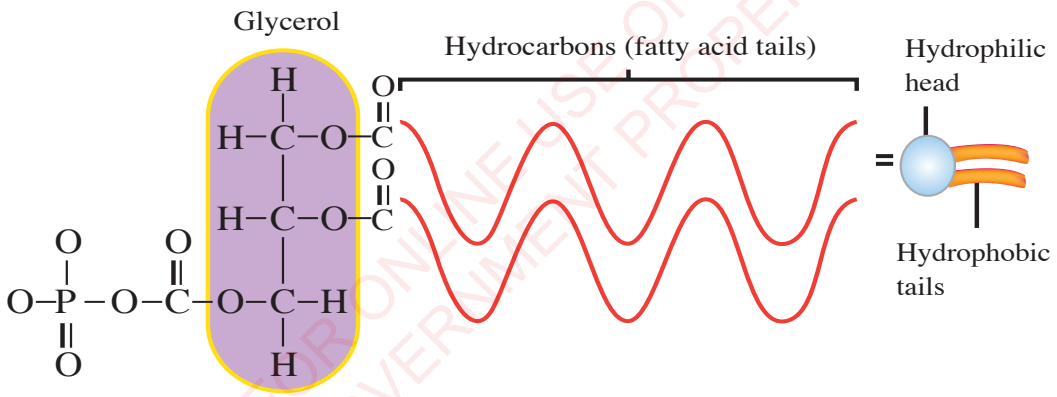


Figure 1.30 Structure of the phospholipid

c) Derived lipids

Derived lipids are substances derived from simple and compound lipids by hydrolysis. The most common derived lipids are steroids, terpenes, and carotenoids.

Steroids. These do not contain fatty acids. and are non saponifiable and not hydrolysed on heating. They are widely distributed in animals, where they are associated with physiological processes. Examples: hormones, oestrogen, progesterone and testosterone.

Terpenes. They are essential oils in plants found particularly in conifers, citrus trees and some insects. They are used for formation of aroma into medicine, such as aromatherapy, perfume and food additives. These include certain fat soluble vitamins, such as vitamins A, E, and K.

Carotenoids. These are widely distributed in both plants and animals. They are exclusively of plant origin. Due to the presence of many conjugated double bonds, they are coloured red or yellow. Examples are lycopene, carotenes, and xanthophyll (oxygenated derivatives of carotenes).

Properties of lipids

Lipids are either liquids or non-crystalline solids at room temperature. Pure fats or oils are colourless, odourless, and tasteless. They are less dense than water and are esters of alcohols and acids. Simple lipids, such as fats are esters of fatty acids and glycerol. Lipids are insoluble in water, but soluble in organic solvents such as ether, toluene and chloroform. They can be hydrolysed by alkaline compounds into their constituents' components by the process known as saponification. Simple lipids such as fats and oils are hydrolysed by the lipase enzyme into fatty acids and glycerol. Lipids contain either saturated or unsaturated hydrocarbon chains and have a high calorific value due to the presence of large number of hydrogen atoms in their hydrocarbon chains. They are poor heat and electric conductors. Forthis reason, they are functional parts of nerve cells and skin sub-cutaneous layer.

Biochemical test for lipids

Lipids are nonpolar and do not dissolve in polar solvents, such as water. They only dissolve in nonpolar solvents, such as benzene, ether, absolute alcohols, and chloroform. This property makes the lipids to be tested effectively by adding nonpolar dye, which can easily be absorbed by a nonpolar lipids. Lipids can be tested using several methods, including that which involves the use of Sudan III solution, the grease spot test and emulsification test (Table 1.5).

The basis of the tests

Fat globules are stained red with Sudan III solution. Being less dense than water and insoluble in water, a red stained oil layer floats on the surface of water. In addition, with grease spot test, fats or oil droplets create a translucent spots on the paper on warming. As already known that, lipids are immiscible with water, therefore addition of water to a solution mixture of lipids and ethanol results into emulsion of tiny droplets in the water, which reflect light, giving a white opalescent appearance. Emulsification process is permanent and complete in the presence of emulsifying agents, such as bile salts, soap and protein. This process is important in fat digestion in the intestine, as the emulsifying agents (bile salts) lower surface tension of the lipids and increase the surface area, hence easily acted by digestive enzymes.

Table 1.5 Biochemical test for lipids

Food sample to be tested	Procedure	Observation	Inference
Lipid (fat or oil)	**Sudan III test** Put 2 ml of a solution containing lipid in a clean and dry test tube. Add 3 drops of Sudan III solution and shake vigorously. Then allows the mixture to settle for 1 minute.	A red- stained oil layer separates on the surface of solution.	Lipids present.
	Grease spot test Rub a drop of the sample on to a piece of paper. Allow time for any water to evaporate. Warm gently in order to speed up the process or reaction.	A permanent translucent spot on the paper.	Lipids present.
	Emulsification test Put 2 ml of absolute ethanol in a clean and dry test tube, and then add 2 ml of lipid. Shake vigorously to dissolve the lipids. Then add equal volume of cold water.	Lipids becomes finely divided and is dispersed in water when shaken with water it forms a cloudy white suspension (emulsification).	Lipids present.

Functions of lipids

a) They are structural component of membranes. Examples: phospholipids and glycolipids.

b) They insulate the body against heat loss. For example, fats found in the sub- cutaneous layer of the skin are an insulating blanket.

c) They are sources of energy; therefore, they are used as alternative respiratory substrates when carbohydrates are completely exhausted.

d) They are sources of metabolic water. This is an important source of water for animals found in arid and semi-arid areas such as camels.

e) Since lipids are less dense than water, they aid in buoyancy in the aquatic animals such as whales.

f) They are precursors of important body requirements such as vitamin D and sex hormones.

g) They protect internal vital organs such as heart and kidneys.

h) They form protective layers against water loss for example waxes in plants.

i) They facilitate fast conduction of nerve impulses, as they are integral parts of myelinated nerve fibres.

j) They are components of some enzyme systems.

k) They form plasma proteins, such as lipoproteins which facilitate transportation of lipids in the aqueous environment of the body.

Activity 1.6 Biochemical test for lipids

Materials

Groundnuts, test tubes, test tube racks, test tube brush, beaker, measuring cylinder, droppers, mortar and pestle, reagents Sudan III solution and distilled water.

Procedure

a) Prepare a solution from the nuts using the materials provided.

b) Carry out a biochemical test to identify food substance(s) present in the solution using the reagents provided.

c) Record your observations.

Exercise 1.12

1. Give an account on the properties of lipids.
2. Classify lipids based on their chemical composition.
3. Describe the structural functions of lipids in living organisms.

1.4.3 Proteins

Proteins are large biomolecules or macromolecules, consisting of one or more long chains of amino acids. A molecule contains carbon, hydrogen, oxygen, nitrogen, sulphur and sometimes phosphorous. The amino group (NH_2) provides protein's basic nature, and the carboxyl group (-COOH) gives the acidic nature of the amino acid. The R-group is known as the side chain which represents the hydrogen atom or any other group such as the alkyl group (Figure 1.31). Proteins differ from one another, primarily in their sequence of amino acids, which is dictated by the nucleotide sequence of their genes and which usually results in protein folding into specific three-dimension structure that determines its activity.

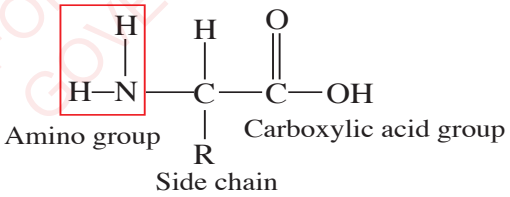


Figure 1.31 Structure of the amino acids

Properties of the amino acids

They are colourless, crystalline solids which are soluble in water but insoluble in organic solvent such as ether, chloroform, and acetone. They are amphoteric compounds as they have both acidic and basic properties. In neutral aqueous solutions, they exist as dipolar or zwitterions. On one side, the acidic carboxyl group has a tendency of donating hydrogen ion (proton); therefore, it dissociates, to release hydrogen ion and becomes negatively charged. On the other side, the basic amino group has a high affinity to hydrogen; therefore, it accepts hydrogen ion and becomes positively charged. Each amino acid has its own pH value at which it exists in its neutral zwitterionic form. This pH at which the amino acids are electrically neutral is termed as an Isoelectric point (I.E.P). In the alkaline medium, when the pH of the I.E.P increases, the amino group dissociates, releasing hydrogen ions, (H^+), the amino acid thus becomes negatively charged. In the acidic medium, (when the pH is lowered), the carboxyl group accepts hydrogen ions, and the whole structure becomes positively charged (Figure 1.32).

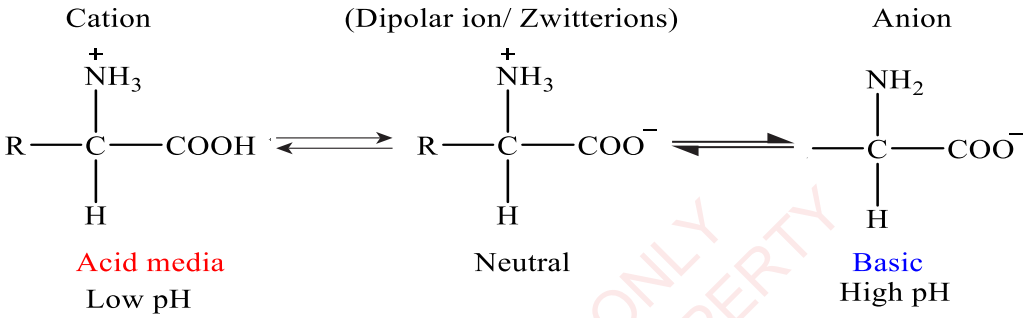


Figure 1.32 Structure of the zwitterion

Formation of proteins

All proteins are formed by condensation of amino acids to give peptide chains. The condensation reaction occurs between the amino group of one amino acid and the carboxylic group of other amino acid to form a dipeptide molecule linked by peptide bond (Figure 1.33). Further combination of this type extends the length of the chain to form a polypeptide chain, which usually contains hundreds of amino acids. Polypeptides may be linked by other forces such as disulphide bridges, hydrogen bond, hydrophobic interaction and ionic bonds.

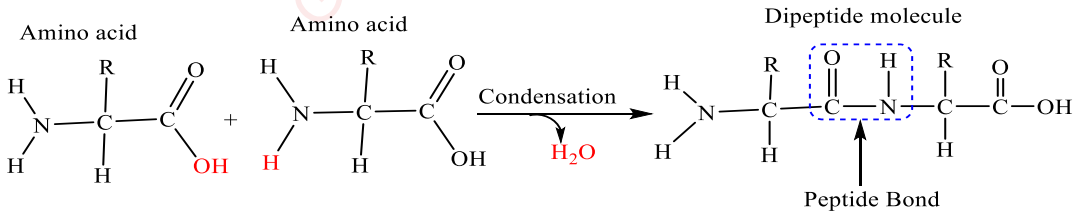


Figure 1.33 Formation of dipeptide molecule linked by the peptide bond

Structure of polypeptide

The structure of polypeptide molecule is determined by amino acids sequences and its configuration. For each particular type of protein, the chain of amino acid makes up a polypeptide molecule of a specific shape. This shape is very important in the functioning of the protein, especially enzymes. The type and the three-dimension configuration of a polypeptide molecule, is stabilised by the interactions of five different types of bonds (Figure 1.35).

Peptide bond

This is a bond formed between carboxyl group (-COOH) of one amino acid and amino group ($-NH_2$) of another amino acid. A polypeptide molecule has a free amino group at one end, and a carboxyl group at the other end.

Hydrogen bond

Hydrogen bond is a bond that is formed in the polypeptide chain between amino acid and side (R) groups. The bond is an electrostatic attraction between the hydrogen atom and another electronegative atom. Hydrogen bond forms between the carbonyl (C=O) of one amino acid or the amino group (N-H) of another amino acid. Hydrogen present in hydroxyl (-OH) group or amino group ($-NH_2$) of amino acids, become slightly electropositive. Therefore, hydrogen bond is a partially electrostatic attraction between the hydrogen (H) atom which is covalently bound to a more electronegative atom or group, such as nitrogen (N) and oxygen (O). Although hydrogen bonds are very weak, the absolute number of bonds plays a considerable role in shape and stability of the polypeptide molecule.

Disulphide bond

This is formed between side chains of cysteine (amino acid containing sulphur) and keeps parts of polypeptide intact and maintains its stability. If two molecules of cysteine line up alongside with each other, the neighbouring sulphur can be oxidized to form a disulphide bridge. A disulphide linkage may be formed between the cysteine residues of the same polypeptide chain or different polypeptide chains of a functional protein. Disulphide bonds stabilize the tertiary or quaternary structures of the protein.

Ionic bond

The bond occurs between the positively and negatively charged side chains of amino acids that come in contact with each other. Normally ionic bond is formed between ions of opposite charges from ionized acid ($-COO^-$) and basic ($-NH_3^+$) groups of the amino acids. The availability of ionized carboxylic group (COO^-) and amino group ($-NH_3^+$) at the side chain of amino acid, and at the terminal of polypeptide chain may form ionic interactions, which help to make a polypeptide molecule of a particular shape.

Hydrophobic interaction

This is considered to be among the major driving force for the folding of globular proteins in aqueous environment. Some R groups of amino acids are non-polar as they have equal number of charges from amino and carboxyl groups. The non-polar R groups are hydrophobic and they repel

from water. In a long polypeptide chain, there are many such non-polar amino acids which may occur adjacent to each other. In an aqueous environment such as inside the cell, the linear polypeptide will fold into a particular shape that hydrophobic amino acids come in contact with each other, while excluding water due to its hydrophobicity.

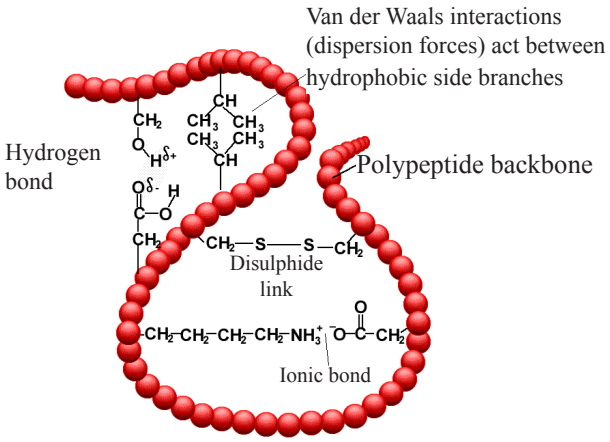


Figure1.34 Bonds in a polypeptide molecule

Categories of proteins

Due to their complexity, it is difficult to classify protein molecules into a single, well defined category. They can be classified according to their structure, composition, level of organisation, and functions.

a) Classification of proteins based on their structure

Based on their structure, proteins are categorized as fibrous, globular, and intermediate proteins.

Fibrous proteins. These proteins form long polypeptide chains, cross linked at intervals, forming long fibres or sheets (Figure 1.35). Their shapes resemble long ribbons or fibres. Fibrous proteins are mostly found in animals, and are usually insoluble in water as well as in other aqueous media. Fibrous proteins aid in protection and structural support. Examples of fibrous proteins include collagen (tendons, bones, and other connective tissues), myosin (found in muscles) and keratin (found in nails, horns, hairs, fur, and feathers).

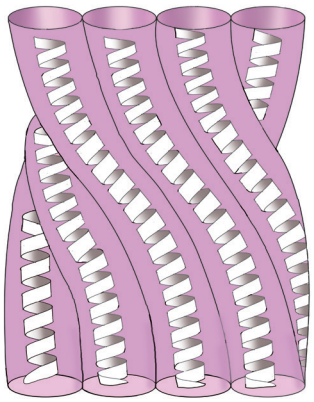


Figure 1.35 Structure of fibrous proteins (α-keratin)

Globular proteins. These proteins have tertiary structure, in which the polypeptide chains are tightly folded to form the spherical shape (Figure 1.36). They are soluble in water. Examples of such proteins include enzymes, antibodies, and some hormones, such as insulin.

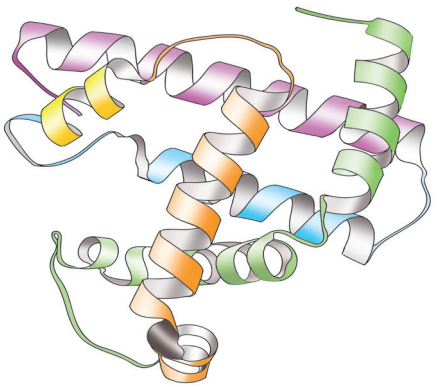


Figure 1.36 Structure of globular proteins

Intermediate proteins. These are fibrous, soluble proteins. A good example of intermediate proteins is fibrinogen, which forms an insoluble fibrin during blood clotting.

b) Classification of proteins based on their composition

Based on their composition, proteins can be classified as simple and conjugated or complex proteins.

Simple proteins. These are proteins made up of only amino acids, and are mostly globular. When decomposed by acids, these proteins liberate their constituent amino acids. Examples of simple proteins are albumins, globulins, and histones.

Conjugated proteins. These are proteins made up of amino acids and other organic compounds. They have a non-amino acid group termed as prosthetic group. Examples of conjugate proteins and their prosthetic groups are shown in Table 1.6.

Table 1.6 Conjugate proteins, their prosthetic groups, and locations

Name	Prosthetic group	Location
Phosphoprotein	Phosphoric acid	Casein of milk and vitelline of egg yolk.
Glycoprotein	Carbohydrate	Cell membrane, and mucin (component of saliva).
Nucleoprotein	Nucleic acid	Component in the structures of viruses, chromosomes and ribosomes.
Lipoprotein	Lipid	Cell membrane and lipids transported in blood as lipoprotein.

c) Classification of proteins based on their level of organisation

There are four types of proteins based on the level of structural organization, namely primary, secondary, tertiary, and quaternary structures of proteins.

Primary structure of proteins. The primary structure of protein is a linear sequence of amino acids that make up the polypeptide chain (Figure 1.37). Its sequence is determined by the sequence of nucleotide bases of the DNA in the genetic code. The amino acid sequence determines the positioning of different R-groups relative to each other. The positioning also determines the way the protein folds and the final structure of the molecule.

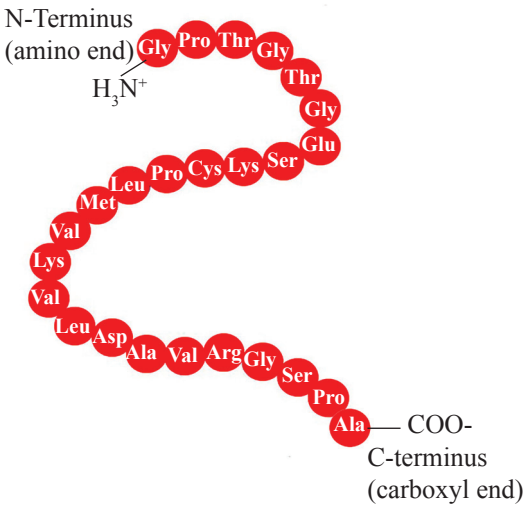


Figure 1.37 The primary structure of proteins

Secondary structure of proteins. The secondary structure of proteins refers to the regular folding pattern of β-sheets and α helix of the polypeptide chain (Figure 1.38). The linear unfolded structure of the polypeptide chain assumes a helical shape to produce the secondary structure. The regular pattern is due to the hydrogen bond formation between atoms of the amino acid and backbone of the polypeptide chain. It includes components of hairs, claws, nails, and the skin.

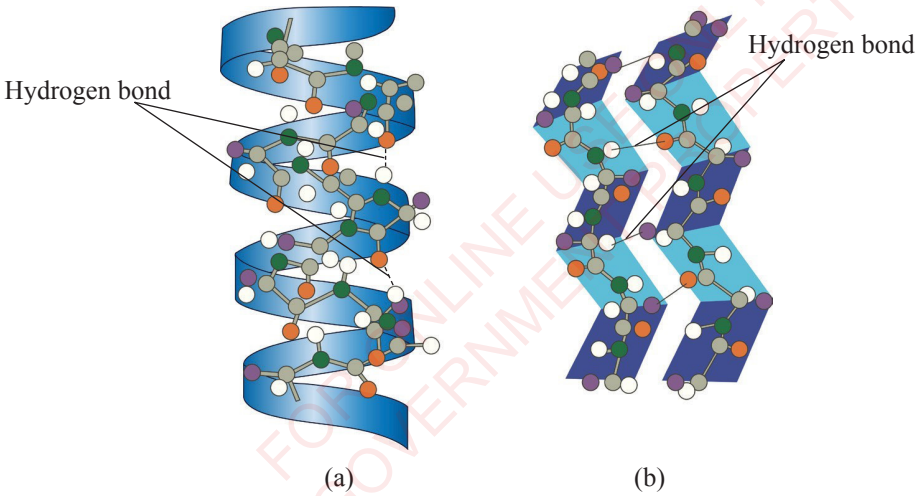


Figure 1.38 The secondary structure of proteins (a) alpha helix and (b) beta plate

Tertiary structure of proteins. The tertiary structure of proteins is the three-dimensional structure formed by the bending and twisting of the polypeptide chain (Figure 1.39). The linear sequence of the polypeptide chain is folded into a compact globular structure. The folding of the polypeptide chain is stabilized by weak, non-covalent interactions. These interactions are hydrogen bonds and

electrostatic interactions. Hydrogen bonds are formed when hydrogen atom is shared with two other atoms. Hydrophobic interactions, disulphide linkages and covalent bonds, also contribute to the formation of the tertiary structure. Examples of tertiary structure proteins are enzymes and antibodies.

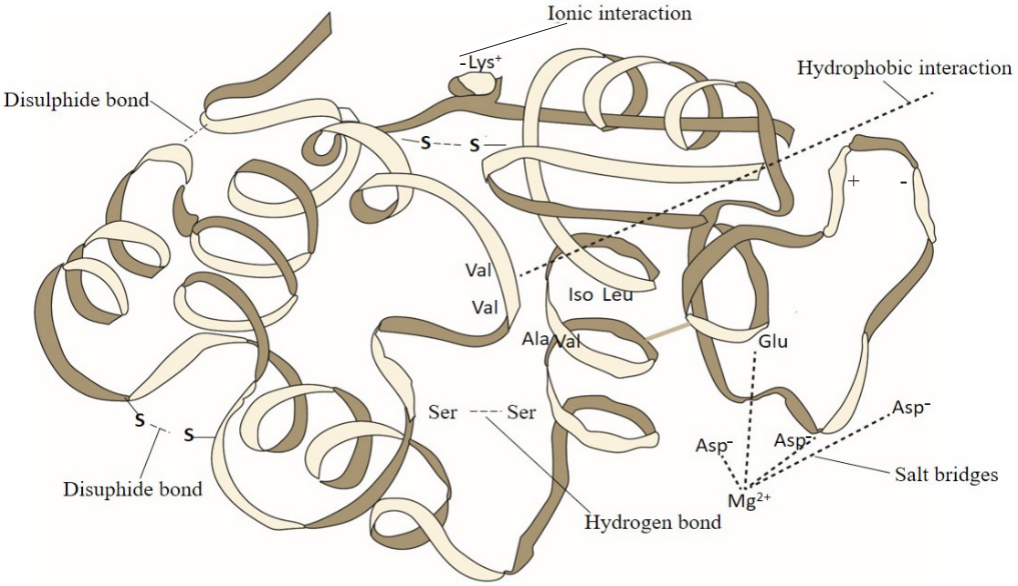


Figure 1.39 The tertiary structure of proteins

Quaternary structure of proteins. Some proteins contain more than one polypeptide chains. This association of polypeptide chains refers to the quaternary structure of proteins and each polypeptide chain is called a subunit. The subunits can be similar or different. For example, haemoglobin which is the oxygen carrying component of the blood, is made up of four polypeptide chains; 2α-chains, each containing 141 amino acids, and 2β chains, each containing 146 amino acids (Figure 1.40).

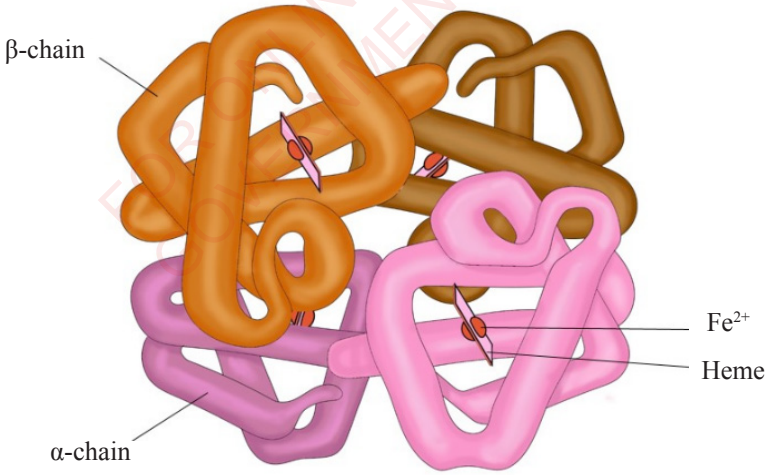


Figure 1.40 The quaternary structure of proteins

d) Classification of proteins according to their functions

Proteins can be classified into different categories depending on their physical and chemical structures as well as their location in the cell. They can also be grouped based on the metabolic functions they perform in the body as follows:

Enzymes proteins. These are biological catalysts which are mostly protein in nature. They are the most varied and highly specialised proteins with catalytic activity. Virtually, all the chemical reactions of organic biomolecules in cells are catalysed by enzymes, resulting into increased reaction rate. Enzymes such as urease, catalase, and lactase catalyse a variety of body reactions.

Structural proteins. These are proteins which aid in strengthening or protecting biological structures. These protein act as supporting filaments, cables or sheets to give biological structure, strength, and protection. Collagen is an example of the structural protein of the bone and connective tissue. Collagen and elastin provide a fibrous framework in animal connective tissues, such as tendons and ligaments. Keratin is the structural protein of hairs, horns, finger nails, feathers and other skin appendages of animals.

Transport or carrier proteins. These proteins are involved in transportation of ions and other substances. Examples of such proteins include haemoglobin, the iron-containing protein of blood, which transports oxygen from the lungs to other parts of the body, serum albumin which transports fatty acids in the blood, lipoproteins, which carry lipids from the site of absorption or synthesis to the site of utilization or storage and membrane transport proteins which transport substances across the cell membranes.

Nutrient and storage proteins. These are proteins which provide reservoirs of essential nutrients to a growing embryo. A good example is the albumin of an egg white, used as an amino acid source for the developing embryo. Casein, the protein of milk, is the major source of amino acids for baby mammals. Ferritin is an iron-binding protein; which stores iron in the liver. Moreover, plants store proteins in seeds, where seeds of many plants store nutrient protein for growth of embryonic plants such as wheat, rice, maize, and bean.

Contractile or motile proteins. These proteins function in the contractile tissues. They include actin, myosin, and tubulin proteins. They are important for movement of body parts. Contractile proteins are responsible for undulation of the cilia and flagella, which propel many cells.

Defence proteins. These are proteins which defend the body against invaders, such as antibodies, fibrinogen and thrombin. These are highly specialized proteins that recognize and combine with foreign substances like viruses, bacteria and destroy them. Fibrinogen and thrombin are blood clotting proteins which protect the body against excessive bleeding.

Regulatory proteins. They regulate gene expression and cellular or metabolic activities of an organism. These include hormones, such as, insulin hormone which is secreted by the pancreas, helps in the

regulation of the blood sugar concentration that regulates the metabolism of cells. Transcription factors are proteins that regulate gene expression. Some repress gene expression by binding to target genes and activating their transcription. The examples of such protein include lac repressor and catabolite activator protein (CAP). Lac repressor is a DNA-binding protein which inhibits the expression of genes coding for proteins involved in the metabolism of lactose in bacteria, whereas CAP promotes transcription at several sites as it affects the metabolism of sugars and amino acids, protein folding, toxin production and pilus synthesis.

Receptor proteins. Receptor proteins are built into the membrane of a nerve cell and they detect chemical signals released by other nerve cells. Other proteins act as chemical messengers within the brain throughout the body. They are involved in the cell's response to chemical stimuli.

Properties of proteins

Proteins have the following properties:

a) They are colourless, tasteless, and amphoteric in nature as they have both acidic and basic properties derived from –COOH and $–NH_2$ groups respectively.

b) They exhibit characteristic isoelectric points and have buffering properties.

c) They are large molecules; hence, they have high molecular weight. For instance, haemoglobin has the molecular weight of about 68,000 g/mol.

d) Proteins differ in their solubility in water, some are insoluble, example keratin while others are highly soluble such as albumin. Soluble protein can be precipitated from solution by addition of certain salts example NaCl and $(NH_4)_2SO_4$. Decrease in solubility occurs due to competition between salt and protein molecules for water as well as a decrease in charge on the protein molecule.

e) Proteins are also coagulated by heat and agents like strong acids, alkali, alcohol, acetone, urea and salts of heavy metal.

f) Proteins are specific in their reactions and substrates they act upon. This property is clearly illustrated by enzymes.

g) Proteins are colloidal in nature, that is, they can be hydrolysed into their amino acid constituents.

h) They can be denatured or changed from their natural state by heat or chemicals.

Denaturation of proteins

A protein is said to be denatured, if it loses its natural three-dimension conformation or shape. This change may be temporary or permanent, but the amino acid sequence of the protein remains intact because the peptide bonds are not cleaved. Denaturation results in the alteration of physical properties of a protein in terms of solubility and other criteria. However, the protein in this situation can no longer carry out its normal biological functions. The causes of this condition include heat and radiation, organic solvents and detergents, highly concentrated salts and strong acids and alkalis. Denaturation is also caused by heavy metals, urea solution and mechanical forces.

Heat and radiations, such as ultra violet rays and infra-red. These supply kinetic energy which causes strong vibrations

of protein molecules. These result into breaking down of ionic and hydrogen bonds that are weaker than peptide bonds, resulting into coagulation of such protein molecules.

Organic solvents and detergents. These reagents disrupt hydrophobic interactions and form bonds with hydrophobic (non-polar) groups. Consequently, this disrupts hydrogen bonds resulting into denaturation. An example of such chemical substances is methyl alcohol, which is used as a disinfectant to clean the skin before injection. The alcohol denatures proteins in bacterial cell walls.

Highly concentrated salts, strong acids, and alkalis. These compounds disrupt the ionic bonds, resulting into coagulation of proteins. If such proteins remain mixed with these reagents for a long time, peptide bonds may also break down.

Presence of heavy metals such as mercury (Hg), silver (Ag), and lead (Pb). Cations of such metals tend to form strong bonds with the negatively charged carboxyl groups on the proteins, leading to the disruption of ionic bonds. The protein's polarity is reduced and its insolubility becomes high, hence precipitated as an insoluble metal protein.

Urea solution. Urea tends to disrupt hydrogen bonds. Being amide-like, it forms hydrogen bonds of its own via distorting the unique configuration of the protein molecule.

Mechanical forces. Physical movement of proteins may break hydrogen bonds. For example, stretching of hair breaks the hydrogen bonds in the keratin helix. The latter is extended and the hair is stretched. If released, the hair returns to its normal length. However, if it is wetted and then dried under tension, it keeps its new length. This is the basis for hair styling. Many liquid proteins denature and precipitate when they are vigorously agitated because of incorporation of air bubbles and adsorption of protein molecules to the air-liquid interface.

General functions of proteins

a) They are essential building materials of the body. For that reason, they are needed for proper growth and development. This explains why kwashiorkor victims experience stunted growth.

b) They are used as alternative respiratory substrates when both carbohydrates and lipids are completely exhausted.

c) They absorb excess fluids in the body. For example, kwashiorkor victims have swollen lower parts of their legs and some parts of hands due to accumulation of excess fluids, this condition is called oedema.

d) They form structural components of body parts. For instance, keratin is a structural protein of hair, horns, hooves, and nails.

e) They are structural components of membranes. For example, globular protein and glycoprotein which form the cell surface membrane.

f) They take part in various metabolic processes in the body, for example enzymes that catalyse different physiological activities in the body.

g) Proteins such as hormones have the following roles: act as chemical messengers and regulate body metabolites. Examples of such proteins are insulin and glucagon, which regulate the level of blood sugar in mammals.

h) Proteins such as anti-bodies protect the body against infections.

i) Proteins such as myosin and actin are contractile; therefore, they interact to bring about contraction and relaxation of muscles, hence, the movement of body parts and locomotion of animals.

j) Proteins such as haemoglobin and myoglobin transport oxygen in the blood.

k) Proteins such as fibrinogen are important for blood clotting, hence, they help in healing wounds by forming fibres over injured parts to prevent excessive loss of blood and water, and entry of germs.

l) Proteins such as ovalbumin of egg white and casein of milk are storage in function. For example albumin supplies food to a developing embryo.

m) Proteins help to build and improve the body immune system. This explains why children suffering from kwashiorkor are vulnerable to various opportunistic diseases.

Biochemical test for proteins

Proteins are complex organic structures made up of polypeptide chains of amino acids, which have different amino acid sequences and three dimensional configuration to define a particular type of protein. An amino acid is a class of organic compounds with a carboxyl group (-COOH), an amino group (NH_2) and a side group, all attached to a central carbon atom. Proteins differ from each other in terms of their type, number and sequence of amino acids that make up the polypeptide backbone. Therefore, different proteins have different molecular structures, nutritional attributes and physiochemical properties. There are several methods used to test for proteins. The most common method is chemical method. Chemical method relies on the properties of amino acids or peptide bonds that are common to all proteins. The biuret test is a chemical assay that is widely used to detect the presence of proteins and amino acids in a sample. The test relies on a color change to confirm the presence of proteins. If proteins are present, the sample will turn violet (Table 1.7).

The basis of tests

Biuret test is the chemical test used to detect the presence of peptide bond as a general test for detection of proteins. In the presence of dilute copper (II) sulphate ($CuSO_4$) in alkaline solution (medium), nitrogen atoms in the peptide chain form a purple complex with Copper (II) ions (Cu^{2+}).

Table 1.7 Biuret test for protein

Food sample to be tested	Procedure	Observation	Inference
Protein	Prepare a solution of egg albumen. Place 2 ml of egg albumen solution in a clean and dry test tube. Add 2 ml of dilute Sodium hydroxide solution and mix. Then add 2 drops of 1% of Copper (II) sulphate solution and shake (No heating is required).	A purple colour develops slowly	Protein present.

Activity 1.7 Biochemical test for proteins

Materials

Fresh milk, test tube, test tube rack, test tube brush, beaker, measuring cylinder, and dropper, 1% Copper (II) sulphate solution, and dilute sodium hydroxide solution.

Procedure

a) You are provided with a beaker containing fresh milk.

b) Using the apparati and reagents provided, design an experiment and carry out biochemical tests to identify the food substances present in it.

c) Tabulate your results in a usual way to show the procedures followed, observations made, and inferences drawn.

Questions

1. What is the basis of test for the food substance(s) present in the food sample provided?
2. Explain the nutritional roles of the food substance(s) present in the food sample.

Exercise 1.13

1. Proteins are said to be amphoteric in nature, what is the biological importance of this?
2. Explain the medical importance of protein denaturation.
3. Classify proteins on the basis of structure and function.

1.4.4 Enzymes

Enzymes are complex, three dimension globular proteins that are made up by living cells. They are biological catalysts, since they alter the rate of different physiological processes in living organisms. They are also found in natural secretions, such as plant juices, milk and the digestive juices where they catalyse several metabolic reactions or processes taking place in the

living cells. A compound with which the enzyme combines is called a substrate. The substrate fixes itself in an active site of the enzyme whose shape is ideal for accommodating it. The active site is a group of amino acids comprising the region of the enzyme into which the substrate fits in order to catalyse the reaction. By acting as catalysts, enzymes lower the activation energy. Activation energy is the minimum amount of energy that is required to activate a substrate molecule to a condition in which they can undergo biological transformation (Figure 1.41).

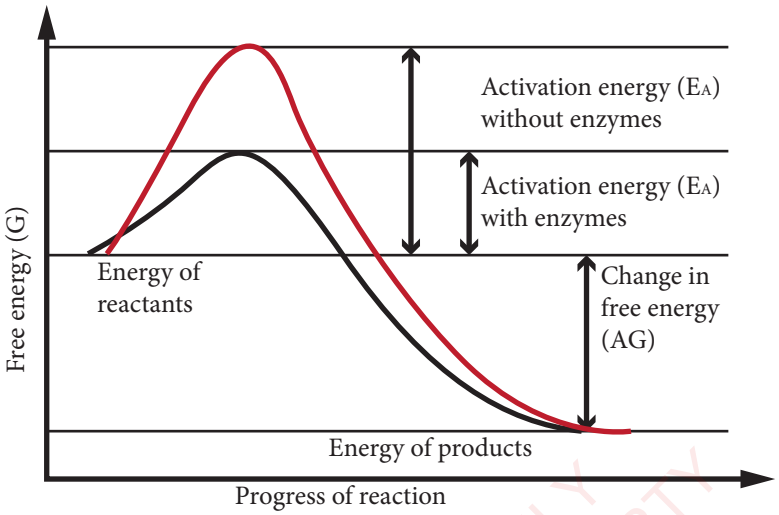


Figure 1.41 Activation energy for an enzyme-catalysed and an un-catalysed reaction

Mechanisms for enzyme action

Several steps of enzymic action result in the formation of products. There are two theories which explains the mechanism of enzymic action. These are the lock and key hypothesis and the induced fit hypothesis. In the lock and key hypothesis, an enzyme holds the substrate as a lock holds the key, while the induced fit hypothesis, the active site expands and contracts to form enzyme - substrate interaction. The two molecules form a temporary structure called an enzyme-substrate complex as an intermediate product of substrate to be converted into product. The products have different shapes from the substrates; therefore, once the product is formed, it escape from the active site, leaving it free for accommodating other substrate molecules.

$$\underset{\text{Enzyme}}{E} + \underset{\text{Substrate}}{S} \longrightarrow \underset{\text{Enzyme-substrate complex}}{ES} \longrightarrow \underset{\text{Enzyme-product complex}}{EP} \longrightarrow \underset{\text{Enzyme}}{E} + \underset{\text{product}}{P}$$

Lock and Key theory

The theory states that, as the key fits in one lock, the same happens to a substrate which fits only in one active site of the enzyme to form an enzyme-substrate complex (Figure 1.42). The specific action of an enzyme with a single substrate can be explained using a Lock and Key analogy first postulated in 1894 by Emil Fischer. In this analogy, the lock is the enzyme and the key is the substrate. Only the correctly sized key (substrate) fits into the key hole (active site) of the lock (enzyme). Smaller keys, larger keys, or incorrectly positioned teeth on keys (incorrectly shaped or sized substrate molecules) do not fit into the lock (enzyme). Only the correctly shaped key opens a particular lock.

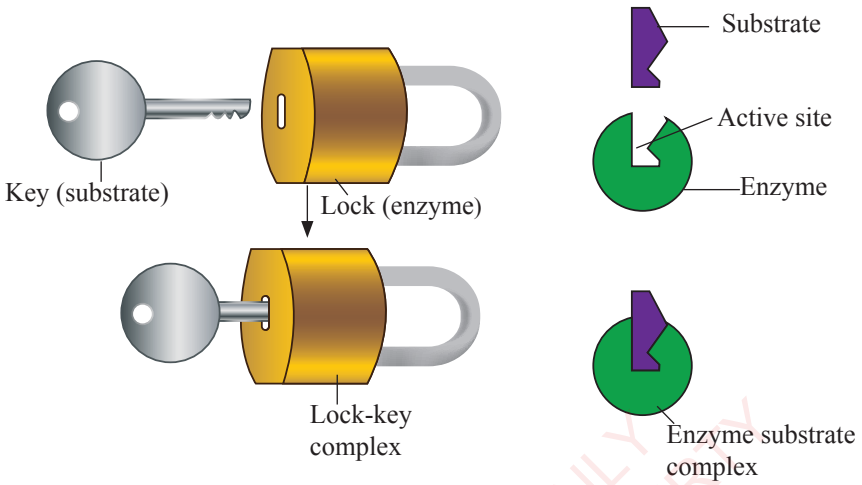


Figure 1.42 A model explaining the lock and key hypothesis

Induced fit theory

The induced-fit theory assumes that the substrate plays a role in determining the final shape of the enzyme; thus, the enzyme is partially flexible (Figure 1.43). This explains why certain compounds can bind to the enzyme but do not react because the enzyme has been distorted too much. Other molecules may be too small to induce the proper alignment. Therefore, they cannot react, since only the specific substrate is capable of inducing the proper alignment of the active site.

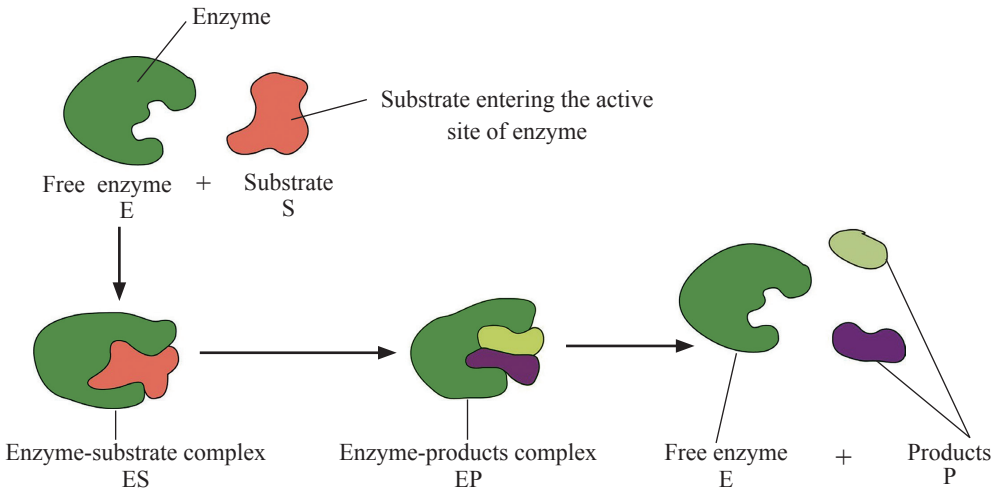


Figure 1.43 Model of induced fit theory

Factors governing rate of enzyme activity

Several factors affect enzyme activities. These include substrate concentration, enzyme concentration, temperature, and pH level.

a) Substrate concentration

At fixed concentration of enzymes, an increase in substrate concentration will increase the rate of reaction. This is because more substrate molecules will be colliding with enzyme molecules. Therefore, more products will be formed at a time. However, after a certain concentration, any increase will have no effect on the rate of reaction, since all enzyme's active sites have bound to substrate, and the remaining substrate will be unable to bind to enzymes.

This point is called enzyme saturation point. Thus, extra substrates have to wait for the enzyme to release the product and become free to accommodate other substrate (Figure 1.44).

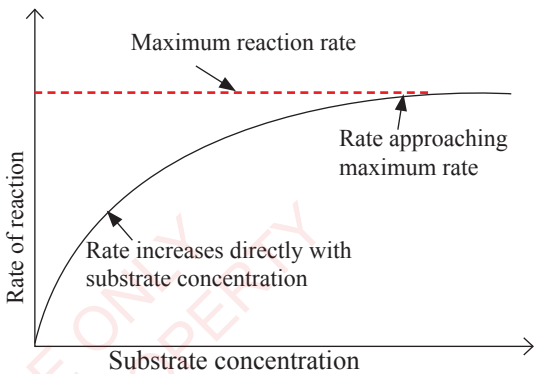


Figure 1.44 The effect of substrate concentration on the reaction rate of enzyme

b) Enzyme concentration

The rate of any enzyme catalysed reaction directly depends on the concentration of the enzymes. Provided that, the temperature and other conditions are suitable for reaction and there are excess substrate molecules, the rate of the reaction is directly proportional to the concentration of enzymes. If the amount of the substrate is restricted, it may limit the rate of the reaction. Likewise, addition of more enzymes cannot increase the rate. Therefore, the graph tails off as shown in Figure1.45.

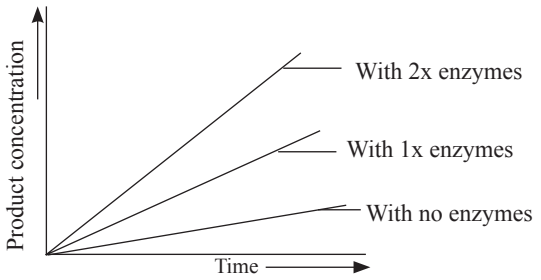


Figure 1.45 The effect of enzyme concentration on the reaction rate of enzyme controlled reaction

c) Temperature

Generally, increase in temperature increases the kinetic energy that molecules possess, implying more random collisions between molecules per unit time. Since enzymes catalyse reactions by randomly colliding with substrate molecules, increasing temperature will increase the rate of reaction, leading to more products. However, increasing temperature also increases the vibration energy that molecules have; specifically in case of enzyme molecules which put strain on the bonds that hold them together. As temperature increases, more bonds, especially the weaker hydrogen and ionic bonds, will break because of this strain. Breaking of bonds within the enzyme will cause the active site to change in shape. This change in shape means that the active site is less complementary to the shape of the substrate; therefore, it is less likely to catalyse the reaction. The change in shape prevents the enzyme and substrate from fitting together exactly. Finally, the enzyme will become denatured, and it will no longer be functional, hence decreasing the rate of reaction.

However, below normal temperature, enzymes become less active due to reduction in speed of molecular movement. When the temperature is lowered below or near freezing point, the enzymes are said to be inactive. This condition will last when the higher temperature above the freezing point is restored.

Therefore, as the temperature increases, the rate of reaction also increases due to increased kinetic energy. There is a temperature range at which the rate of enzyme's action is maximum. This is called an optimum temperature. Below this temperature, enzymes are less active. Contrary, above the optimum temperature, enzymes are denatured. All enzymes work within a range of temperature specific to the organism. In human, the optimum temperature for many enzymes lies around 40 °C and denaturation occurs at about 60 °C (Figure 1.46). However, enzymes of some other organisms have different optimum temperatures. For example thermophilic bacteria such as *Thermus aquaticus* have optimum enzymatic temperature ranges from 51 °C to 80 °C and in *Archaea* the optimum enzymic temperature ranges from 41 °C to 122 °C.

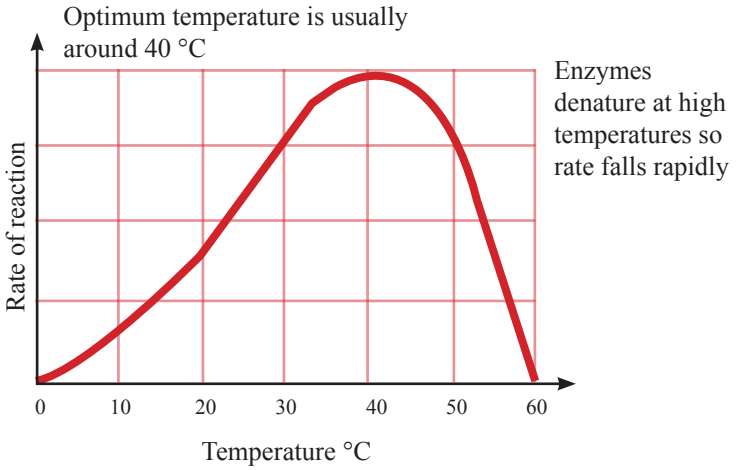


Figure 1.46 Effect of temperature on the rate of an enzyme-controlled reaction

The effect of temperature on the rate of reaction can be expressed as temperature coefficient, Q_{10}. According to the Q_{10} rule, the rate of a physiological process or reaction doubles for every 10 °C rise in temperature, if the temperature is within the range that can be tolerated by a living system. A mathematical expression is presented below:

$$Q_{10} = \frac{\text{rate of reaction at (X+10) °C}}{\text{rate of reaction at X °C}}$$

Where: X is the initial temperature

Thus, within the range of 0 - 40 °C, Q_{10} of an enzyme controlled reaction is 2.

This means that the rate of the enzyme's action doubles for every 10 °C rise in temperature.

d) pH

The pH scale measures the acidity and basicity of a solution. pH is a measure of hydrogen ion (H^+) concentration. It is therefore a good indicator of the hydroxy ion (OH^-) concentration. Its values ranges from 1 to 14. Lower pH values implies higher H^+ concentration and lower OH^- concentration. Acidic solutions have pH values below 7, and basic solutions (alkalis) have pH values above 7 while the pH of 7 is termed as 'neutral'. Hydrogen (H^+) and hydroxyl (OH^-) ions are charged, therefore, they interfere with hydrogen and ionic bonds that hold together an enzyme, since they will be attracted or repelled by the charges created by the bonds. This interference causes a change in shape of the enzyme and, consequently, its active site. Most enzymes are sensitive to pH and have specific ranges of activity. Different enzymes have different optimum pH values; hence, the bonds within them are influenced by H^+ and OH^- ions at different pH value. Thus, the shape of their active site is most complementary to the shape of their substrate.

At optimum pH, the rate of reaction is maximum. Any change in pH, above or below the optimum, will quickly cause a decrease in the rate of reaction, since more enzyme molecules will have active sites whose shapes are not less complementary to the shape of their substrates (Figure 1.47). Slight changes in pH above or below the optimum do not cause a permanent change to

the enzyme, since the bonds can be reformed. However, extreme changes in pH can cause enzymes to be denatured and permanently lose their functions. Enzymes in different locations have different optimum pH values, since their environmental conditions may differ. For example, the enzyme "pepsin" functions best at pH value of around 2 and is found in the stomach which contains hydrochloric acid. "Carbonic anhydrase" which is a key enzyme in all living organisms works best at pH value of around 7, and "chymotrypsin" which is found in small intestine works best at pH value of around 9.

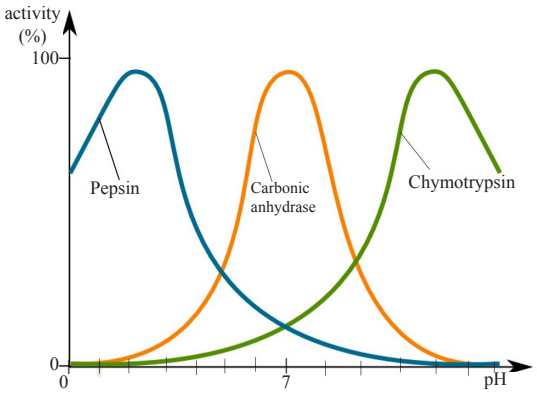


Figure 1.47 The effect of pH on the rate of an enzyme-controlled reaction

Enzyme cofactors

Many enzyme-catalysed reactions require more than just an enzyme and its substrate. Some enzymes require a particular ion or even a small molecule known as cofactor. Cofactors are small, non-protein components of enzymes that are needed for their efficient activity. These substances are stable at high temperatures and vary from simple inorganic ions to complex organic compounds. In such enzymes, the protein part is called an apoenzyme and the non-protein groups that are associated with the enzyme are known as prosthetic groups. Only apoenzyme and cofactor together are active as a catalyst. The cofactor is either inorganic ions, usually metal ions such as Fe^{2+}, Mg^{2+}, Cu^{2+}, Cl^- or small organic molecules such as haem, biotin, Flavine adenine dinucleotide (FAD), Nicotineamide adenine dinucleotide (NAD). They may also be vitamins called coenzymes. Some enzymes need both, a metal ions and a coenzyme to become active.

Metal ion and/or coenzyme

Apoenzyme + Cofactor = Active enzyme

Enzymes inhibitors

There are many molecules that can interfere with enzymes activity either by reducing or destroying their actions. These molecules are called enzyme inhibitors. There are two main groups of inhibitors: competitive and non-competitive inhibitors. In either type, inhibitors are either reversible or irreversible. Reversible inhibitors generally bind to an enzyme with weak bonds, such as hydrogen bonds, which are easily broken. The effect of these inhibitors to the enzyme is temporary, such that, when they are detached, the enzyme regains its normal functioning. Contrary, irreversible inhibitors are strongly bonded to the enzyme in such a way that an enzyme and the inhibitor cannot be separated without damaging the enzyme.

Competitive inhibitors resemble substrates, therefore, they compete with the substrates for the active site of an enzyme molecule

(Figure 1.48a). When the inhibitor remains fixed to the active site, the enzyme is prevented from working normally, as the substrate cannot move into the active site. The substrate is then prevented from binding to the same active site and therefore, decreases the enzyme affinity to other substrates. The effects of competitive inhibitors decrease with increased concentration of substrates. A good example of the competitive inhibitors is malonic acid, which competes with succinic acid for the active site of a respiratory enzyme, succinic dehydrogenase.

Non-competitive inhibitors are substances that do not resemble substrates. Therefore, they neither compete for nor attach to the active site of the enzyme. They fix themselves elsewhere on the enzyme molecule. In so doing, they completely alter the shape of the enzyme molecule in such a way that the active site cannot accommodate the substrate. Since the inhibitor does not compete with the substrates for the active site of the enzyme, an increase in substrate concentration does not reduce the effect of the non competitive inhibitor. An example of non-competitive inhibitor is cyanide, which attaches itself to copper prosthetic group of cytochrome oxidases, thereby inhibiting respiration process (Figure 1. 48b).

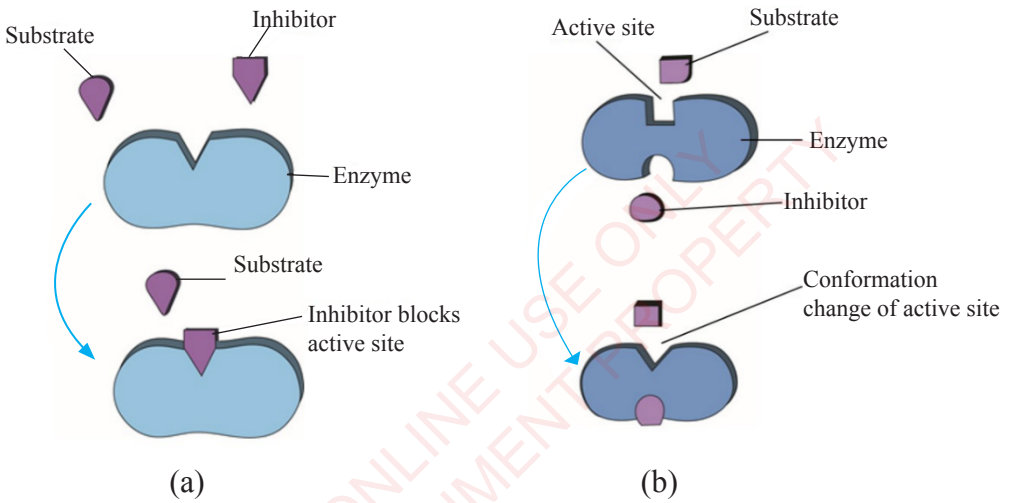


Figure 1.48 Inhibitors (a) competitive (b) non-competitive

Enzyme regulation

Regulation of enzymatic activity is an important biological activity in controlling different metabolic processes. Enzymes are important for regulation of different metabolic activities, such as biochemical pathways, homeostasis, gastro intestinal digestion and growth. The common way in which metabolic pathways in the cells are regulated involve allosteric enzymes which are designed to change the shape and are regulated by the compounds which act as non-competitive inhibitors. The regulation of these enzymatic activities includes; end-product inhibition, zymogens and genetic control.

End-product inhibition control. If a given physiological process involves several steps and various intermediates, the end product of the pathway may inhibit the enzyme at the start (Figure 1.49). In this example, the product "Y" acts as an inhibitor to enzyme "a" (ea). If the level of product Y falls, the inhibition is reduced. If the level of Y rises above normal, inhibition of "ea" increases; therefore, the level of Y is reduced. In this way, homeostatic control of Y is achieved. This mechanism is termed as negative feedback, because the information from the end of the pathway which is feedback to the start has a negative effect; that is the high concentration of Y reduces its own production rate. The enzymes that are inhibited in this way are called allosteric enzymes. These enzymes can have more than one shape. One shape renders the enzyme active (by allosteric activator), another renders it inactive (by allosteric inhibitor).

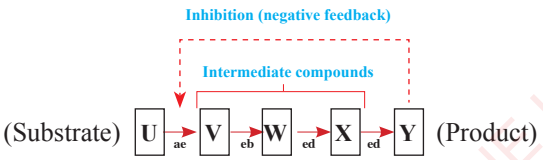


Figure 1.49 End product inhibition of enzyme

Zymogens (proenzymes) control. Some enzymes are synthesized in inactive forms that differ in composition from the active forms. Activation of such enzymes, known as zymogens or proenzymes, requires a chemical reaction that either adds or splits off part of the molecule. Some enzymes that digest proteins, examples: trypsinogen, chemotrypsinogen, and proelastase are produced in the pancreas. These enzymes must be inactive when they are synthesized, so that they cannot attack the pancreas.

Genetic control. This is the regulation of enzymatic activity by control of the synthesis of the enzyme. The synthesis of enzymes is regulated by genes. Genes carry the code for making enzymes. These mechanisms, which are controlled by hormones can accelerate or decelerate enzyme synthesis. The genetic control strategy is particularly useful for enzymes which are needed only at certain stages of development. Depending on the genetics and other environmental factors, the body can produce many enzymes during a lifetime. As body ageing commences, the body tries to automatically conserve its decreasing resources and produces fewer enzymes of all types. When this lifetime enzyme potential is reached, the body can no longer sustain life. Death occurs because nothing takes place in the body without enzymes. Enzymes constitute the ``life force" which powers the whole system in the organism's life expectance.

Properties of enzymes

They are proteins (globular proteins) in nature and biocatalysts, as they lower the activation energy of the reaction they catalyse. They are never used up, never affected by the reaction they catalyse, meaning that it remains unchanged at the end of reaction. Since they are proteins, enzymes are coded for by DNA. They have active sites where the substrates are accommodated; and the sites have specific shapes which make them to be specific to not only the substrates they act upon, but also the reactions they catalyse. They are sensitive to temperature and pH changes, and they can also be affected by enzyme

and substrate concentration. They are very efficient, thus, they are needed in a very small amount; this means that a small amount of enzymes acts on large quantities of substrates. Enzymes work reversibly; meaning that they catalyse reversible reactions. For example, an enzyme carbonic anhydrase catalyses the combination of carbondioxide and water to form carbonic acid in tissues where the concentration of carbon dioxide is high. In the lungs, where the concentration of carbon dioxide is low, the same carbonic anhydrase, catalyses the dissociation of carbonic acid into carbon dioxide and water.

Classification of enzymes

In 1964, the International Union of Biochemistry (IUB) introduced a system of classifying enzymes based on the type of reactions they catalyse. This system recognised six major functional classes of enzymes.

a) **Oxidoreductases** which catalyse redox reactions (biological oxidation and reduction reactions) by the transfer of hydrogen, oxygen, or electrons from one molecule to another. Example;

$$\text{Ethanal + NADH + H}^{+} \xleftrightarrow{\text{dehydrogenase}} \text{Ethanol + NAD}^{+}$$

Hydrogen is simultaneously lost from NADH and gained by ethanal. NADH is oxidised to NAD^{+} and ethanal is reduced to ethanol.

b) **Transferases** which catalyse the transfer of a group from one compound to another. Example;

$$\text{Glutamic asid + Pyruvic} \xrightarrow{\text{aminotransferase}} \text{α-ketoglutaric acid + alanine}$$

The R-group on the amino acid, glutamic acid, is exchanged with the R-group on a keto acid, pyruvic acid. A new amino acid, alanine is formed along with a new keto acid, α-ketoglutaric acid.

c) **Hydrolases** which catalyse the splitting of a large substrate molecule into two smaller products in the presence of water (hydrolysis process).
Example;

$$\text{Lactose + Water} \xrightarrow{\text{Lactase}} \text{Glucose + Galactose}$$

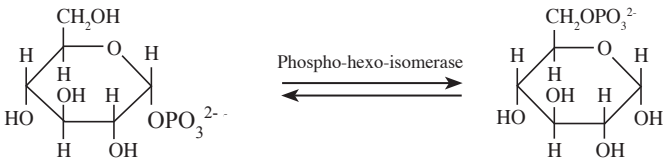
The disaccharide, lactose, is broken down into two monosaccharide residues by the lactase enzyme in the presence of water. All digestive enzymes fall under this category.

d) **Lyases** which catalyse the removal of a chemical group by the process other than hydrolysis.
Example;

$$\text{Pyruvic acid} \xrightarrow{\text{decarboxylase}} \text{Ethanal + Carbon dioxide}$$

Pyruvic acid is converted into ethanal and carbon dioxide by breakage of its double bond.

e) **Isomerases** which catalyse rearrangement within a molecule, converting one isomer to another. For example, glucose-1-phosphate is converted into glucose-6-phosphate in the presence of the phospho-hexo-isomerase enzyme. The position of the phosphate group in the glucose-1-phosphate molecule is changed to form the isomer glucose-6-phosphate.



Glucose - 1 - phosphate Glucose - 6 - phosphate

f) **Ligases** which catalyse the joining of two molecules by forming a new chemical bond, and it requires energy from the breaking down of ATP. An example of such enzymes is amino acyl-tRNA systhetase which catalyses the formation of amino acid-tRNA complex during protein synthesis.

Exercise 1.14

1. Describe the factors governing enzyme activity.
2. Explain how the lock and key hypothesis illustrates specificity of enzymes.
3. Classify enzymes on the basis of reactions they catalyse.
4. Explain why substrate concentration has no effect on non-competitive inhibition.
5. Explain why at temperatures above 40 °C, mammalian enzymes do not function efficiently?

1.4.5 Adenosine Triphosphate (ATP)

ATP is a nucleoside triphosphate used in cells, often called the "molecular unit of currency" of intracellular energy transfer. It belongs to a category of high energy compounds that release energy when the bond between the second and third phosphate is broken. The presence of these high energy bonds makes it possible for ATP to store and release energy for cellular reactions.

Chemical composition

ATP consists of adenosine (composed of an adenine ring and a five carbon sugar, ribose sugar) and three phosphate groups (triphosphate) (Figure 1.50). ATP is highly soluble in water and is quite stable in solutions with pH ranging between 6.8 and 7.4, but easily hydrolysed at extreme

pH. Therefore, ATP is best stored as an anhydrous salt. It is also considered as the energy currency of the cell and life, because all cells need this energy molecule in order to perform their functions in the human body.

Formation of ATP

One molecule of ATP contains three phosphate groups, and is produced by a wide variety of enzymes, including ATP synthase, from adenosine diphosphate (ADP) or adenosine monophosphate (AMP) and various phosphate group donors.

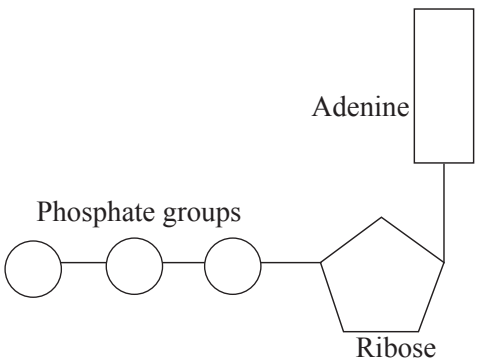


Figure 1.50 The chemical structure of adenosine triphosphate

Synthesis of ATP

ATP is synthesised when an inorganic phosphate, Pi, is energetically bonded to adenosine diphosphate, ADP. The amount of energy required in this process is 30.6kJ.

$$30.6\ kJ + ADP + Pi \xrightarrow{Condensation} ATP + H_2O$$

The processes that yield ATP, therefore, involve phosphorylation. They are of two types:

a) Photosynthetic phosphorylation, ATP is synthesised during light dependent phase of photosynthesis. In this case, when light of appropriate wavelength strikes on the chlorophyll, its electrons get excited, as they gain excess energy. In this state, they are boosted to high energy levels. As the electrons move downhill back to ground state, they lose the gained excess energy, which is used to combine ADP and Pi to form ATP. This process is called photophosphorylation (refer section 5.2).

b) Respiratory phosphorylation, which is the cellular process involving two stages. The first stage is substrate level phosphorylation in which ATP is synthesised in the cytoplasm, by glycolytic pathway. The second stage is oxidative phosphorylation, which occurs in the electron transport system in the inner mitochondrial membranes.

Roles of ATP

ATP provides energy for the following:

a) Synthesis of macromolecules, such as polysaccharides from monosaccharides, proteins from amino acids and DNA replication.

b) Active transport across the plasma membranes in the cell, example: sodium-potassium pump.

c) Cellular movements, such as cilia action in trachea and fallopian tubes, spindle fibers during cell division and muscle contraction.

d) Production of useful secretions by vesicles.

e) Activation of important molecules, such as glucose, which is activated into glucose-6-phosphate during respiration.

Exercise 1.15

1. What is ATP?
2. Briefly explain the process of ATP formation.
3. What is the importance of ATP in our daily life?

1.5 Water as a constituent of the cell

Water is the most abundant molecule in a cell, constituting about 80% of total volume of cell. The liquid part of the cell is called cytosol. Generally, without water, life would not exist on this planet as water supports metabolic reactions.

Properties of water

Water is an excellent solvent for polar compounds such as ionic substances, like salts, and non-ionic substances like sugars. It has a high heat of vaporization due to hydrogen bonds which hold molecules together. Latent heat of vaporization means a measure of the heat energy required to overcome the attractive forces between molecules and make them to escape in form of a gas (vaporize). This property is significant in minimizing water loss from the body and cooling it.

Water has high heat capacity which is the heat required to raise the temperature of 1 kilogram of water by 1^0C. By having high heat capacity means that, increase in heat energy can lead to relatively small rise in temperature. Also water has a high heat of fusion. It requires a relatively large amount of energy to melt its solid state (the ice). Conversely, liquid water must lose a relatively large amount of heat energy to freeze. Thus, this property is important in maintaining natural states of cell contents. Water has a density of 1000 kgm^{-3} or 1 gcm^{-3} at standard temperature and pressure. However, the density decreases with a decrease in temperature. Thus, frozen water (ice) floats on liquid water. Water has a high surface tension and cohesive force. Cohesive force is the force by which individual molecules stick together.

Water being liquid at room temperature, provides a liquid environment inside the cells. Example glycolysis and synthesis of proteins that take place in the cytoplasm. Additionally, water has a high latent heat of vaporisation. This means that water needs a lot of energy to evaporate hence, helps in cooling the body through sweating.

Roles of water

The roles of water in living organisms can be categorized as follows:

The metabolic role of water

a) It is used for hydrolysis of many substances, such as proteins into amino acids, fats into fatty acids and glycerol. In the hydrolytic processes, water is brought in by enzymes or hydrolytic reagents such as mineral acids.

b) It is the medium for all cellular metabolic processes, for instance, water is an important raw material for photosynthesis.

c) It facilitates diffusion of materials across surfaces; for example, for passage of food solutions into blood stream across the walls of the ileum.

Water as solvent

Water is a universal solvent; it readily dissolves other substances, hence it is used for the following purposes:

a) For transportation of various substances from one part of the body to another. These are carried by blood and other fluids in solution.

b) For removal of metabolic wastes, such as nitrogenous waste products. These excretory wastes are removed from the body in the form of solution in water.

Water as a lubricant

Due to its viscosity property, water takes part in lubricating body parts which slide past each other. It makes various lubricating fluids in the body; example: mucus, which aids movements in animals such as snails. It also lubricates internal parts, such as gut walls in animals, the synovial fluid (which lubricates movements in joints of vertebrates) and pleural fluid (which lubricates movements of lungs during breathing).

Supporting role of water

The supporting role of water is made clear in the following examples:

a) In animals such as annelids and nematodes, water exerts a hydrostatic pressure which helps to support and maintain their structure. This is known as the hydrostatic skeleton.

b) Osmotic influx of water into plant cells generates turgor pressure which supports herbaceous (non-woody) plants. The turgor pressure also supports primary growth in woody plants.

c) Water found in humours of the eye helps to maintain the eye's shape.

d) The mammalian foetus is supported and protected by an amniotic fluid, which is largely water.

e) Water provides support (habitat) to aquatic organisms such as fish.

Other functions

Other functions of water include the following:

a) It controls body temperature in mammals. Evaporation of sweat from the body surface has the cooling effect.

b) It is an agent for dispersal of seeds, larvae, and male gametes of animals and lower plants such as Bryophytes.

c) In mammals, fluids in the inner ear are important for hearing and balance.

Exercise 1.16

1. Explain the role of water in plants and animals.
2. Water is said to be the universal solvent. Substantiate.
3. Explain the properties of water.

Revision questions

1. Why is a mitochondrion said to be a cell within a cell?
2. Explain the prokaryotic nature of the mitochondrion and chloroplast.
3. Chloroplast, mitochondria, and bacteria have features in common. Substantiate.
4. Explain the role of the following cell organelles:
   a) Lysosomes
   b) Endoplasmic reticulum
   c) Ribosome
   d) Golgi apparatus
5. With the aid of diagrams, differentiate a bacterial cell from a plant cell.
6. Describe the difference in molecular structure between cellulose and starch.
7. Name the bond(s) formed between neighbouring glucose molecules in starch and cellulose.
8. Explain why amylase, the enzyme that catalyses the hydrolysis of starch, will not catalyse the hydrolysis of cellulose.
9. Compare the lock and key hypothesis and the induced fit hypothesis of enzymes' action.
10. Outline the uses of ATP in the metabolic activity of the cell(s).

Chapter Two

Principles of classification

Introduction

Planet Earth contains different kinds of organisms, ranging in size from microorganisms to macroorganisms. Due to the existing diversity of organisms, it is difficult to clearly understand their characteristics and how they are related in evolutionary terms. Classification helps in identification of organisms that share common characteristics and traits. In this chapter, you will learn about the concept of classification, classification systems, categories of classification, taxonomic ranks, nomenclature and taxonomic keys.

2.1 The concept of classification

The science of classification of living organisms dates back to 384-322 BC, when the first taxonomist, Aristotle initially classified organisms into two major groups, namely animals and plants. With advances in science and technology, classification has constantly been dynamic and more refined. For example, by using electron microscope and molecular techniques, taxonomists have classified organisms into five kingdoms namely Monera, Protoctista, Fungi, Plantae, and Animalia. Considering the fact that the number of organisms occupying the earth is large, it has been difficult for scientists to study each individual organism. Since related organisms share some common features, scientists group related organisms together so that they can easily study their characteristics.

The process of grouping organisms based on their common or shared characteristics is called classification. For organisms to be classified uniformly across the world, a set of principles, procedures, and rules must be observed. The principles of classification were pioneered by Carolus Linnaeus and published in the 18th century in his book *"Systema Naturae"*. In that publication a simple way of naming organisms was also explained. The science of classifying organisms is termed taxonomy and the scientist who classifies organisms is known as a taxonomist. Taxonomy involves placing organisms into their respective groups and sub groups called taxa without considering evolution. The science of placing organisms in their respective taxa that reflect their evolutionary history is called systematics.

Importance of classification of organisms

The importance of classification of organisms is summarised as follows:

a) It helps to reduce large number of groups of dissimilar organisms into small number of manageable groups of organisms with more features in common. For example, all species of flower producing plants are placed under division Angiospermophyta. Similarly, all species of non flowering plants are placed in division Coniferophyta and all spore producing plant species with conductive tissues are placed in division Filicinophyta. Once plant species are grouped in this way, it makes it easy to understand their life cycle.

b) It makes easy to classify all known organisms and predict the placement of the yet to be discovered based on already known features. For example, if a new plant species with flowers is discovered today it will be placed under division Angiospermophyta. Similarly, if it produces flowers, leaves, berries and stems with stipules as those of coffee plants; it will be placed under the coffee family Rubiaceae. Furthermore, if it has more features in common with *Coffea arabica* it will definitely be placed under genus *Coffea*, making its classification simple and less time consuming.

c) Classification simplifies communication among taxonomists worldwide. This is because, taxonomically, an organism is assigned only one name, unlike the use of common names in which one species is named differently in different places. *Zea mays* is a scientific name for maize. In America, maize is also known as corn but in Britain corn is wheat which sounds confusing. However, *Zea mays* worldwide will only refer to different names of what we call maize in Tanzania.

d) It helps to show evolutionary relationship between organisms. The classification of organisms is mostly based on evolutionary history and relationship among them. This makes it easy to understand how organisms are related interms of their evolutionary history. A Leopard (*Panthera pardus*) and Lion (*Panthera leo*) which are both classified under family Felidae and genus *Panthera* have a lot of features in common. These are hairs, mammary glands, and other various morphological features. It is therefore most likely that they share a common ancestor.

e) Organisms grouped in the same taxon, such as at genus level, normally have many common features. For example, all plant species under genus *Coffea* resemble coffee plants in many aspects, such as leaf type, leaf arrangement on stems, flower type, and stipules. They all differ from members of cotton plants, genus *Gossypium* on the same features. This kind of grouping therefore simplifies description of organisms because understanding of features of just one individual within a certain group/taxon can give an insight into all other members within the same taxon.

f) It paves a way towards understanding other disciplines, such as ecology, medicine and pharmacy. For example, plants of the same genus may have similar ecological or growth requirements. Ecologically, all plants under the bean/legume family (Leguminosae/Fabaceae) have the ability to harbour Nitrogen fixing bacteria. Likewise, members under the same genus may produce secondary metabolites or biochemicals with similar medicinal or pharmacological properties.

2.2 Classification systems

Organisms can be grouped in many ways for convenience of studying them and to fully appreciate their comparative evolutionary relatedness. Traditionally, all organisms were grouped by Aristotle as either animals or plants with just a few sub groups in each group. This classification had shortfalls as it did not consider the evolutionary relationship among organisms grouped together. For example, grouping into one or single group of all flying animals such as birds, bats, moths and butterflies, as done by Aristotle was taxonomically misleading. This is because bats are actually mammals with hairs on their bodies and they differ from birds which have feathers. They also differ from the butterflies, which are insects. A penguin which has feathers would be difficult to classify it with birds into the same group as it lacks the ability to fly.

The controversy of classification was partly resolved by the taxonomist Carolus Linnaeus in the 1700s. This taxonomist retained the two major groups or kingdoms of organisms, Animalia and Plantae. Linnaeus introduced several taxa under each kingdom to accommodate groups of organisms sharing more common characteristics in which resemblance among organisms increased hierarchically down the groups. He classified organisms based on their shared natural features.

Since then, classification has been very dynamic, and has gone through five systems. These are artificial, natural, phyletic, phenetics and phylogenetics or cladistics. In artificial approach, only one or a few observable characteristics were used. Natural approach grouped together individuals reflecting how they occur in nature. This approach did not reflect evolutionary history though it used many characteristics. Natural approach was followed by phyletic approach based on Charles Darwin's publication; "The origin of species by means of natural selection" and the development of modern theory of chromosomes. In phyletic system organisms were classified from simple to complex, reflecting evolutionary history. However, assigning of ancestral or derived status was done subjectively. Phyletic was followed by phenetic approach. Phenetics uses many characteristics and mathematical algorithms to group similar organisms in same cluster and different organisms in different clusters. As in natural system, phenetics does not consider evolutionary history. The most recent approach is known as phylogenetic. This approach

bring together organisms that share derived characters in groups called clades. Clades thus are made up of organisms that share the most recent ancestor.

The change from one approach to the next was influenced by advances in science and technology leading to use of new source of taxonomic data, methods of analysis and weaknesses observed in previous approach. Phylogenetic approach use DNA markers and different computer software and analysis programs.

Types of classification systems

There are two major systems of classification; artificial and natural system of classification.

Artificial system of classification

This system of classification uses a few easily observable characteristics to classify organisms for easy and quick comparison or study. Examples of artificial classification could be when grouping all animals as fauna and all plants as flora, or when grouping all organisms on the basis of their body size as microorganisms and macroorganisms. Other examples are when grouping animals as flying and non-flying animals, edible versus non-edible plants, spices versus non-spices plants, predators versus prey animals, and medicinal versus non-medicinal plants. As noted from the above examples, this system of classification neglects natural relationship existing among these groups of organisms. For instance, birds and bats are all flying animals, but the former have feathers while the latter have hairs and mammary glands. Similarly, medicinal plants producing flowers, seeds, and fruits are different from spore producing medicinal plants. Thus, the medicinal value attached to these plants cannot suffice their placement in one group because they have no shared natural features. This limits the application of this classification system despite its significant merits. Artificial system cannot group individuals that are evolutionary related. As a result all classfication systems that does not reflect evolutionary history are considered to be artificial.

Merits of artificial system of classification

a) It is simple to identify and classify organisms since newly discovered organisms with just a few known information can be easily fitted in. It therefore takes short time in placing an organism into its group.

b) It is stable; it does not change with time or discovery of new organisms given its broad nature of classification.

c) It is less expensive; since it uses few observable features to group the organism.

d) This system does not require special classification techniques or skilled personnel.

Demerits of artificial system of classification

a) It does not consider evolutionary or phylogenetic relationship among organisms. Closely related organisms under the artificial system are most likely to be placed in different groups while unrelated organisms such as bats and birds may be grouped together because both have wings. This makes

the system somewhat misleading because, phylogenetically, organisms belonging to one group would be expected to have originated from a common ancestor.

b) It provides only a limited characteristics or information about each member. For example, organisms such as viruses, bacteria and some fungi are grouped as microorganisms because they are microscopic. This classification has ignored other features like their modes of feeding, reproduction, and cell structure. Use of these features necessitate grouping of these microorganisms in different groups.

c) It does not allow the prediction of information, hence it limits recent advancements in taxonomy.

d) It does not incorporate new discoveries. New species cannot be easily added to the existing groups.

The natural system of classification

The natural system of classification is the system of grouping organisms based on natural features they have in common, particularly those that reflects the evolutionary relationship. Characters that show evolutionary relationship are shared derived ones which are many and are shared aross members of one group With advances in science and technology, the natural system of classification has incorporated anatomical, embryological, serology, physiological, and molecular characteristics and techniques in grouping organisms.

Merits of natural system of classification

a) It allows organisms which are genetically and evolutionarily related to be grouped in the same taxon, the evolutionary relatedness increases down the hierarchy. This clearly implies that organisms grouped together at genus level will be more evolutionarily related than those grouped at family level.

b) This classification system considers homology of all characters of organisms which makes it easy to predict information about missing links in the course of evolution of organisms even though there is no fossil evidence to substantiate the link. For example, some taxonomists have predicted that flowering plants evolved from Pteridosperms, a seeded fern which is not existing.

c) It allows critical thinking and development of inquiry minds. Although description based on morphological, physiological, anatomical, and embryological features of a newly discovered species has to be done before a decision on its proper placement to a taxon is reached.

d) It is accurate, since it involves plenty of scientific research to gather enough information before the actual placement of an organism to a particular taxon is decided.

Demerits of natural system of classification

a) It makes classification of organisms tedious, expensive and time consuming. It is very difficult, since it

requires much information to place the organisms into their respective groups. Newly identified organisms are thus not easily classified.

b) It is not stable; it changes with the increasing diversity of organisms and new discoveries based on expanding knowledge, science and technology. It was the discovery of the light microscope that led to the discovery of kingdom Protista. Later, with the invention of the scan electron microscope, it made it easy to separate Archaeae and Eubacteria into different groups within the same kingdom Monera.

c) Given the wealth of information, knowledge, techniques, and skills required to classify organisms, natural classification is limited to taxonomic experts.

Activity 2.1 Classification of living organisms

Materials

Earthworms, a *Pinus* branch, a fern plant (*Dryopteris* sp. or *Pteridium aquilinum*), a grasshopper, a butterfly, a young maize plant, mature bean plant, a mouse, grass (*Panicum* sp. or *Hyparrhenia* sp.), a housefly, tilapia, a hand lens, a note book, pen, and pencil.

Procedure

a) Collect the above mentioned specimens.

b) Observe each specimen carefully and use the provided hand lens where necessary, then answer the questions that follow.

Questions

1. Record any three observable features of each specimen.
2. Classify all the specimens into two major groups, citing the criteria used to classify them.
3. Using the features recorded in number 1 above, classify the collected organisms into any three broad groups and state the criteria used to classify them.
4. Classify all the specimens into five groups. Give reason for your classification.
5. Give any two reasons to justify the placement of the species in the above five groups.
6. Briefly comment on the evolutionary relationship among the organisms placed in the same group as in question 5.

Safety precautions

Necessary precautions should be observed when collecting specimens from the school surroundings and nearby environment since there might be dangerous organisms like snakes, bees, thorn plants, and allergens.

2.3 Taxonomic ranks

The classification system by Carolus Linnaeus in 1700s introduced a systematic way of grouping organisms stepwise, from a very broad group of organisms called Kingdom to narrow level of individual organism called species. Linnaeus, recognizing the natural variations existing among organisms divided them into five broad groups. He arranged them hierarchically from the broadest to the smallest in terms of the number of organisms in each. Originally, these groups were Kingdom, Class, Order, Genus (singular) Genera (plural), and Species. However, later on, two more groups were introduced. The first introduced group was called Family, which was created by Michael Adanson in 1763, and it was allocated between order and genus. The second group termed Division or Phylum (singular) phyla (plural) was introduced by Ernest Haeckel in 1866 and it was assigned between kingdom and class, making seven hierarchical groups namely Kingdom, Phylum, Class, Order, Family, Genus, and Species (Figure 2.1), which are still being used by taxonomists today. Phylum is used in animal classification and Division in plant classification. The system in which organisms are classified hierarchically from kingdom to species level is called a taxonomic hierarchy or taxonomic ranking. Any named group or rank within the hierarchy such as kingdom or phylum is referred to as taxon (singular) taxa (plural). A taxonomic rank is therefore a level at which an organism is placed within the hierarchy.

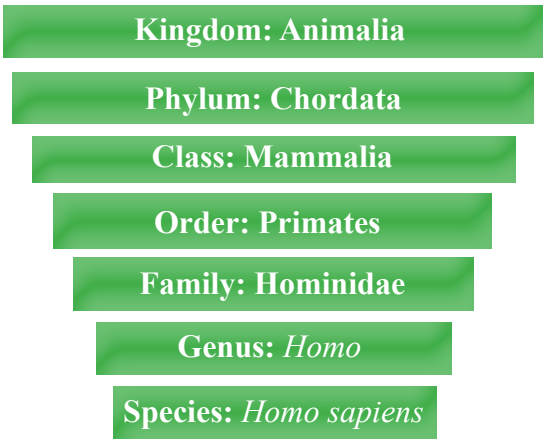


Figure 2.1 Classfication of human being

Organisms placed under the same taxon have features unique to that group; thus, they can be used to describe the entire group. For example, members of same species have the largest number of characters that are more similar and often reproduce fertile offspring. Lions fall in the species *Panthera leo,* leopard in *Panthera pardus,* and tiger *Panthera tigris*. Thus lion, leopard and tiger are different species in the same genus *Panthera*. The genus comprises of relatively more closely related organisms with similar morphology, structure, reproductive organs and most importantly, evolutionary history compared to those at the higher ranks. However, they can not interbred to produce fertile offspring. Members of different related genera fall in one family, families is one order and related orders into one class. Related classes are placed in one phylum/division and related phyla in a kingdom. Kingdom Plantae, for example, contains four divisions, namely Angiospermophyta (Angiosperm), Coniferophyta (Gymnosperm), Pteridophyta or Filicinophyta (Ferns and their relatives), and Bryophyta (Moss).

Kingdom Animalia is made up of Polifera, Cnidaria, Platyhelminthes, Nematoda and its relatives (the round worms), Annelida, Arthropoda, Molusca, Echnodermata, Chordata and several other smaller phyla. Organisms at the rank of kingdom have a few features in common compared to the organisms at lower ranks. This book will focus on five selected phyla of Kingdom Animalia, namely, Platyhelminthes, Nematoda, Annelida, Arthropoda, and Chordata.

Importance of taxonomic hierarchy in classification

a) It provides a standard method to be followed by taxonomists in assigning new scientific names to a newly discovered species. This makes it easy to classify or group organisms.

b) It provides a classification system of living organisms which expresses natural or evolutionary relationship among the members of the same group and between various organisms.

c) It provides smooth communication among the taxonomists, while avoiding confusion and repetition of species names.

d) It simplifies access to information on various organisms across the taxa.

Exercises 2.1

1. Differentiate between artificial and natural systems of classification.
2. Explain the concept of "ranks" as used in classification.
3. Explain what would be the problem if organisms were not grouped into ranks.

2.4 Nomenclature

The process of assigning scientific names to organisms is called nomenclature. The biological nomenclature uses two names that is the generic name representing the name of the genus and specific name representing the species name. The Swedish taxonomist Carolus Linnaeus (1707-1778) is acknowledged for using binomial system consistenty. The word binomial is a combination of two Greek words *bi-nomina* which literally means 'two-names.' Binomial nomenclature follows a set of agreed rules and principles.

2.4.1 Rules used in binomial nomenclature

Binomial nomenclature is governed by nomenclatural codes, which provide details of rules necessary in giving scientific names for various broad groups of organisms, such as animals, plants, fungi algae, bacteria, and virus. For example, the code of nomenclature for wild plants is called the International Code of Botanical Nomenclature (ICBN) while for animals is called the International Code of Zoological Nomenclature (ICZN). The rules used in binomial nomenclature are as follows:

a) The name of an organism should come from its generic and specific name. For example human being belongs to genus *Homo* and species *sapiens*; hence, its scientific name should be *Homo sapiens*. Sweet potato belongs to genus *Ipomoea* and species *batatas*; its scientific name should therefore be *Ipomoea batatas*.

b) The full scientific name should include name of the author; the person who was the first to publish the name effectively. For example, *Rana temporaria* L, where L stands for Linnaeus means Linnaeus was the person who effectively published this name.

c) A specific epithet may be taken from any source and may even be composed arbitrarily.

d) An organism can bear only one correct scientific name, which is the earliest effectively assigned to it, if several names had been given to it earlier.

e) The first name of the binomial, that is the generic name, always begins with a capital letter and the entire species name is written in small letters as in *Pennisetum mezianum*.

f) All binomial names should be written in the Latin language. If the name is hand written, it should be underlined separately or italised in case of a print form. For instance, the scientific name of a leopard can be written as Panthera pardus when hand written or *Panthera pardus* when printed.

g) Any scientific name is not legitimate, unless it is accompanied by a suitable description and a diagnosis which reflects only the unique characteristics of the species.

h) If the binomial name is cited more than once in a paper or report, the genus name can be abbreviated the second time it is written in the same document. In this case, the first letter of the genus is written in a capital letter and separated from species name by a dot. For instance, *Panthera lupus* can be written as *P. lupus* or the bacteria *Escherichia coli* as *E. coli*. The abbreviation "spp." is used to represent several species. In this case, the genus, but not the abbreviation, is italicized or underlined. For instance, *Hyparrhenia* spp. implies several species of the genus *Hyparrhenia* such as *Hyparrhenia rufa, Hyparrhenia collina,* and *Hyparrhenia variabilis*. On the other hand, if the actual specific name cannot be ascertained or specified, an abbreviation "sp" followed by a dot is placed after the generic name, but it is not italicised while the generic name is italicised or underlined, for example, *Hyparrhenia* sp.

Activity 2.2 Binomial nomenclature

Materials

Solanum incanum (thorn apple or bitter ball or bitter apple), *Solanum nigrum* (black nightshade or Hound's berry), *Solanum tuberosum* (irish potato plant).

Procedure

a) Collect the following specimens from the school surroundings or nearby environment: S*olanum incanum, Solanum nigrum,* and *Solanum tuberosum*.

b) Name the genus in which the three collected species belong.

c) Using a magnifying glass where necessary, observe each of the collected plant specimens and state any three natural morphological features justifying the placement in their respective genus.

Questions

1. Which two features would you use to justify the placement of each of the three plants to their species?
2. What two characteristics differentiate the three species from each other.

2.4.2 Significance of scientific names

The use of scientific names is very important for the following reasons:

a) They simplify communication worldwide. This is because only one valid name is used for each living organism.

b) The system provides uniformity in naming organisms worldwide. This helps to avoid confusion and ambiguity.

c) Scientific names are not influenced by language barrier or region as common names.

Exercise 2.2

1. Assume that you are a taxonomist and you want to order some plant species from Tanzania Tree Seeds Agency (TTSA) for the home garden; the species to be ordered are *Lantana camara, Hibiscus* sp. with red flowers, any five panicum species, delonix Regia, jatropha curcas seeds and jatropha curcas stem cuttings.

   a) Write correctly the names of the species to be ordered before submitting to TTSA.

   b) Using your knowledge on the rules of binomial nomenclature explain the violated rules in the above names.

   c) Provide a comprehensive list of the species names to be submitted to TTSA.

2. What do you understand by the following terms:

   a) Nomenclature

   b) Binomial nomenclature.

3. Citing examples of species from your local environment, outline the rules used in binomial nomenclature.
4. Explain the significance of scientific naming of organisms.

2.5 Taxonomic keys

There are several ways of identifying an unidentified organism. Identification is naming an organism based on existing classfication. The easiest way is by consulting and directly asking an expert such as a taxonomist with profound knowledge and experience in identification. Also, by comparing the unidentified organism with authentically identified specimen stored in museums for animals or herbaria for plant specimens. The other way is to use a local field guide in which pictures and/or drawings of organisms coupled with

explanations are available for comparison. Moreover, taxonomic keys may be used for identification of unidentified organisms.

Taxonomic keys are tools or devices used by taxonomists for a quick identification of organisms. The identification is based on permanent contrasting phenotypic features. Phenotypic features, also known as morphological features, include features such as hairs, stipules, shape, number of appendages, and segments. In order to identify an organism using taxonomic keys, all readily observable features of the unknown organisms are recorded first. These are later matched with diagnostic features of a named taxon.

The diagnostic features are characteristics unique to a particular taxon or rank. They differ from those of an organism belonging to a different taxa. Diagnostic features therefore depict natural phylogenetic or evolutionary relationship, and they are reflective of features used in both artificial and natural systems of classification.

Taxonomic keys enable organisms to be identified into their appropriate taxon and it increases familiarity of taxonomist with the identified organisms; since it involves careful investigation of the presence or absence of particular structures and manifestation of present characteristics.

Procedures for construction of taxonomic keys

a) The organisms to be identified are collected and displayed for a thorough observation of identifiable features. The collected organisms, such as, animals and plants are called specimens.

b) Each of the collected specimens is carefully examined, and its easily observable features are identified and recorded in a notebook.

c) A table listing the specimens in one column and characters to be studied in the other is created.

d) From the table, study the recorded specimen features carefully and determine a general pair of exclusion character which can be used to divide the entire group of collected specimens into two.

e) Subdivide each of the obtained groups into two more groups using shared or common features.

f) The second group is subdivided further into two other smaller groups based on their common features.

g) The smaller groups are continuously subdivided into two groups using contrasting pairs of statements or couplets until all of the specimens are identified.

h) If the constructed key is numbered, allocate the number of couplet to be considered next after each step to the last step in which the specimen is identified.

i) Write down the couplets in a special pattern to get a desired framework for a particular key.

Types of taxonomic keys

There are various types of diagnostic keys used in taxonomy. The most common and simple key used for identification of organisms is called dichotomous key. This type of key was pioneered by a French taxonomist, Jean Baptiste Lamark in

1778. *Dichotomous* is a Greek word which literally means 'divided into 2 branches' or 'cut in half.' This kind of key is constructed using two statements with contrasting features and mutually exclusive choices at a branching point. The pair of statements is called leads or couplet, and they provide two alternatives at each branching, each leading to a subsequent statement until an organism is identified. As one moves down the key, a large group of organisms with diverse features is reduced to a smaller group and finally to an individual organism or taxon.

The couplets can be organised using numbers as in numeric keys or letters. It is worth noting that the characteristics used in dichotomous keys may be quantitative or qualitative. The former can be examplified by features such as number of petals, leaf size, and petiole size, while the latter could be leaf shape, stem texture such as woody or herbaceous and flower-colour. In constructing dichotomous keys, features used in describing organisms must be permanent but not temporal or transitional features, such as those emanating from seasonal variations or growth of an organism based on how couplets are organised in directing the user from one choice to the next. Two types of dichotomous keys are recognised. These are indented key and bracketed or simple numbered key.

Indented dichotomous key

In indented dichotomous key pairs of contrasting statements are successively indented, with equal distance from the left. Each statement (or lead) starts with the same character being described, and they both begin with the same noun, such as leaves, corolla, and petiole.

Example: Indented dichotomous key for five plant species

1a. Flowers present	
2a. Leaves small	*Abelia grandiflora*
2b. Leaves large	
3a. Flowers red, petals free	*Hibiscus rosa-sinensis*
3b. Flowers red, petals connate into tube	*Delonix regia*
1b. Flowers absent	
4a. Tree with needle-like leaves	*Pinus sylvestris*
4b. Shrub with leafy fronds	*Dryopteris filix-mas*

Bracketed dichotomous keys

In bracketed dichotomous keys, sets of couplets are kept together (bracketed), and they start at the same level near the margin. The couplets must be assigned numbers or letters. The user is provided with a pair of lead for identification of unidentified organism or taxon and is directed by numbers to a subsequent lead, if the selected lead does not provide the answer.

Example 1: Bracketed dichotomous keys for five plant species

1a. Flowers present 2
1b. Flowers absent 3
2a. Leaves small..... *Abelia grandiflora*
2b. Leaves large 4
3a. Tree with needle-like leaves..... *Pinus sylvestris*
3b. Shrub with leafy fronds..... *Dryopteris filix-mas*
4a. Flowers red, petals free ..... *Hibiscus rosa-sinensis*
4b. Flowers red, petals connate into tube..... *Delonix regia*

Example 2: Bracketed dichotomous keys for seven animal species (Figure 2.2)

1a. Organism has a backbone……2
1b. Organism does not have a backbone……3
2a. Organism has wings……4
2b. Organism does not have wings……5
3a. Organism has antennae …….. Grasshopper
3b. Organism does not have antennae……Spider
4a. Organism has feathers……..Bird
4b. Organism has hair……Bat
5a. Organism has legs……6
5b. Organism does not have legs……Snake
6a. Organism has a shell……Turtle
6b. Organism does not have a shell……Frog

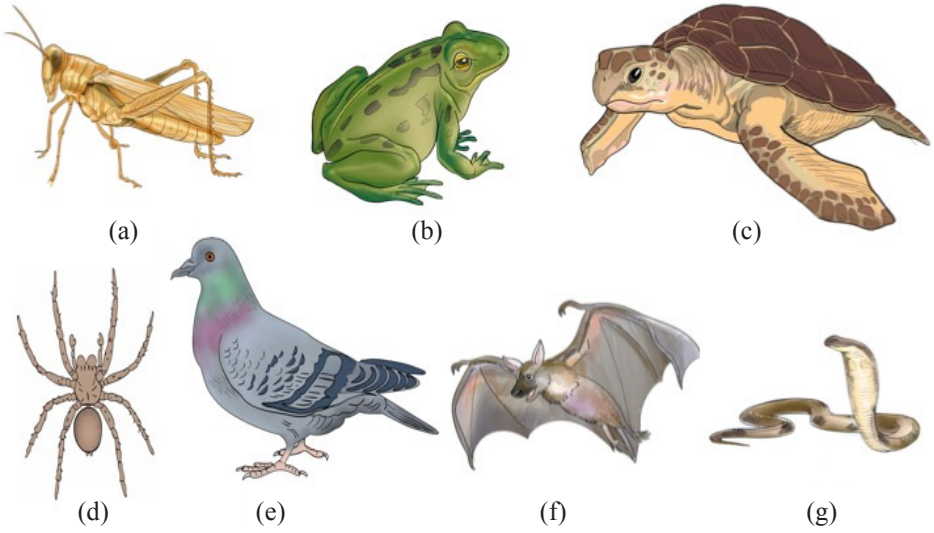


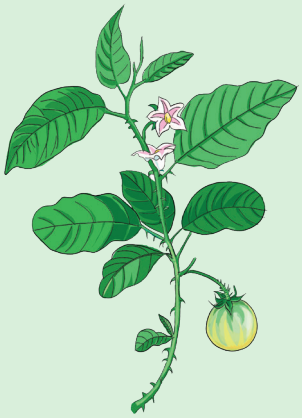
Figure 2.2 Animals (a) grasshopper, b) frog (c) turtle (d) spider (e) bird (f) bat, and (g) snake

Revision questions

1. What is biological classification?
2. Explain any four drawbacks of artificial system of classification.
3. Elucidate the advantages of natural system of classification.
4. With examples, briefly explain why it is important to classify organisms.
5. Explain the significance of taxonomic hierarchy in classification.
6. Explain with examples, scientific and technological advantages paralleled with the taxonomic shift from artificial to natural system of classification.
7. Explain the challenges of assigning scientific name to a newly discovered organisms.
8. Why is scientific naming of organisms important?
9. Citing one example for each, outline rules governing binomial nomenclature.
10. You are provided with fresh specimen of (a*) Phaseolus vulgaris* (bean), (b) *Solanum tuberosum* (irish potato), (c) *Solanum incanum* (bitter ball), (d) *Solanum lycopersicum* (tomato) and (e) *Solanum aethiopicum* (bitter tomato) with flowers (Figure 2.3).
    i) Examine characteristics of each plant species such as the stem texture, leaf blade size, leaf blade margin, flower colour, size of calyx, and size of corolla.
    ii) Construct bracketed and indented keys for identification of the provided specimens.

(a)

(b)



(c)

(d)

(e)

Figure 2.3 Specimens for question number 10

Chapter
Three

Comparative studies of natural groups of organisms

Introduction

In comparative studies of natural groups, organisms are classified on the basis of their shared characteristics and common ancestry. The grouping is done in relation to physiology, embryonic development, and phylogenetic relationship. In this chapter, you will learn the six groups of organisms, namely Viruses, Monera, Protoctista, Fungi, Plantae, and Animalia.

3.1 General overview of classification

The natural groups of organisms are the broad categories of organisms formed by placing together organisms which are naturally or evolutionarily related for comparative purposes. This enables taxonomists across the world to compare for various reasons how individual groups of organisms are related. The number of natural groups of organisms, for example at kingdom level has been steadily increasing since the 18th century, when Carolus Linnaeus introduced the natural classification system from which kingdom Animalia (multicellular heterotrophs) and Plantae (multicellular autotrophs) were conceived. This system was adopted by many taxonomists and gained a wider popularity over the artificial system of classification.

In 1866, the third kingdom of unicellular organisms, Protista was put forward by Ernest Haeckel after its long placement under kingdom Animalia since it was first discovered by Antoine van Leeuwenhoek in 1674. The discovery of the scanning electron microscope facilitated microscopic studies, and it made it possible to discern Eukaryotes (organisms with distinct nucleus) from Prokaryotes (organisms lacking a clearly defined nucleus but have their DNA lying free in the cytoplasm). This led to the establishment of kingdom Monera, in which all types of bacteria were grouped. The placement of multicellular eukaryotic saprophytic organisms such as mushrooms, yeast, and *Rhizopus* was still contradicting, because they were erratically classified under kingdom Plantae or Protista. This prompted Robert Whitaker to propose kingdom Fungi in 1969 under which all

multicellular saprophytes were grouped, making five kingdoms. However, molecular studies by Carl Woese in the 1970s revealed cellular structural differences among prokaryotes based on membrane structure, ribosomal RNA, lipid compounds, among others. This necessitated the splitting of kingdom Monera also called Prokaryota into Archaebacteria and Eubacteria. In 1982, about a decade later, Margulis and Shwartz proposed a classification system which adopted the five kingdoms, namely the Prokaryotae and four Eukaryote kingdoms. However, that was not the end, because recent molecular work has further revealed phylogenetic relatedness among protists which lead to yet another kingdom, Chromista.

In 2015, Cavalier Smith and others introduced biological taxonomy of 8 kingdoms namely; Eubacteria, Archaebacteria (Archae), Archezoa, Protozoa, Chromista, Fungi, Plantae, and Animalia. Biological taxonomy of 8 kingdoms has introduced a taxonomic rank called domain above the kingdom. Three domains of life, namely domain Archaea, Bacteria and Eukarya, are thus recognised. Domain Archaea includes Archaea bacteria which are the most primitive bacteria with cell wall containing pseudomurein but lacking a peptidoglycan cell wall. Domain bacteria consist of all true bacteria, while Eukarya encompasses all Eukaryotic organisms thus bringing together the kingdoms Protoctista, Fungi, Plantae, and Animalia.

3.2 Viruses

The first viruses were isolated in 1852 as infectious extract from tobacco plants suffering from tobacco mosaic. In 1898, Beijerink named the isolated extract *'virus'* a Latin word, meaning toxic or infectious. Viruses are therefore infectious particles, thought to have genomes detached out of eukaryotic or prokaryotic cells. Thus, a virus can be defined as a fragment of nucleic acid (single or double stranded DNA or RNA), surrounded by a protein coat and capable of replicating once they are inside a living cell. Generally, viruses are too minute; they are smaller than bacteria and cannot be seen by a light microscope, but they can be viewed under the electron microscope. The latter has simplified an understanding on the characteristics of viruses, including their shapes and ways in which they interact with their hosts.

Characteristics of viruses

a) They are the smallest organisms with size ranging from 17 nm to 300 nm. On average, they are 50 times smaller than bacteria, which range in size between 0.1–10 µm.

b) They are simple in structure with a fragment of nucleic acid which is either DNA or RNA, enclosed in a protein or lipoprotein layer. Most animal and bacterial viruses have DNA, but other animal and plant viruses have RNA.

c) Viruses lack cellular structure organisation, hence they are acellular.

d) Viruses can reproduce in a living cell only, that is, inside the cell of a living host.

e) Most viruses are infectious; they can cause diseases to their hosts. They show a high degree of host cell specificity, as they can recognise and infect specific

types of host cells. For example, a virus causing disease in plants will not cause disease in animals and vice-versa. However, the same viruses can cause disease to different species in the same group of organisms. A virus called H5-N1 that causes a fatal bird's flu was recently discovered to cause infection and death in humans.

f) In the absence of a host, viruses can crystallize outside a living medium and assume features of non-living organisms.

g) The ability of a virus to reproduce inside the cell and crystallize in the absence of a living host places them between living and non-living organisms.

h) Viruses are obligate endoparasites because they can live and replicate inside their host cell only.

3.2.1 Classification of viruses

Generally, classification of viruses has been challenging due to their characteristics while inside or outside the host cell. Several other attributes of viruses intensify the difficulties experienced by taxonomists in classifying them because they are very microscopic nucleocapsids (they are smaller than a molecule), lack cellular organisation (acellular) and lack certainty in evolutionary history despite having fragments of genetic materials such as DNA or RNA. Thus, they do not fit precisely into the established biological classification system as they possess both living and non-living characteristics.

Living characteristics of viruses

While inside the host cell, viruses possess a number of characteristics similar to those of living organisms as follows:

a) They possess nucleic acid; either DNA or RNA, which is a genetic material helping the virus to produce identical copies of itself.

b) They penetrate through a host cell by the help of enzymes derived from the protein coat on the cell surface of the host cell.

c) They are able to multiply or reproduce inside the host cell.

d) They are able to undergo mutation in response to host internal changes, and they respond rapidly.

e) They possess capsid, which is a protein coat embracing nucleic acids.

f) They show specificity to hosts and have the ability to infect the host cell and take control of its metabolic activity.

Non-living characteristics of viruses

As non-living organisms, viruses have the following characteristics;

a) They do not replicate on their own and lack cellular structures hence unable to carry out any life processes when outside the host cell.

b) They do not have any enzyme system such as respiratory enzyme, hence they lack energy releasing processes.

c) While outside the host cell, viruses are inert, but retain their ability to replicate, if they invade a host cell. Viruses are therefore crystalline in the absence of a host cell. When they exist as individual particles outside the host cell, they are called virions.

d) They are filterable; therefore, they can pass through a bacterial proof filter paper.

e) They are resistant to very high temperatures due to lack of enzymes. Normally, at high temperatures, enzymes are denatured and thus render them useless.

Viruses can be classified based on a number of factors including; phenotypic characteristics, such as type of nucleic acid, host organisms, type of disease they cause, mode of replication, and morphology. In the classification according to type of nucleic acid, there are RNA and DNA viruses. RNA virus is a virus that has RNA as its genetic material, normally single-stranded RNA, but some viruses may form double helix intra-stranded complimentary base pair of RNA. Viruses infect both plants and animals, examples are Tobacco Mosaic Virus (TMV) which infects plants, influenza virus, hepatitis virus, and polio virus which infect humans. A type of RNA virus known as Retrovirus has a peculiar character of inserting a copy of its RNA into DNA of the host cell by reverse transcription process and changing the genetic material of that cell, example is Human Immunodeficiency Virus (HIV). On the other hand, DNA virus is a type of virus whose genetic material is DNA rather than RNA. The DNA may be either double or single stranded. These viruses infect animals and plants. Examples include herpes virus, smallpox virus, chickenpox virus; which infect animals, and tomato yellow leaf curl virus; which infect plants.

Classification according to the host range includes plant viruses which infect plants only. Examples include; Tomato leaf curl virus that infect tomatoes and Tobacco mosaic virus which infect plants like tobacco and other plants including tomato, potato, orchid and blackcurrant, and cauliflower mosaic virus which infect cauliflower plant. In this type also there are animal viruses which infect animals only, examples include influenza virus and Herpes simplex virus which infect human. Also, there are bacteria viruses that infect bacteria, for example; bacteriophage such as lambda (λ) phage (a lysogenic virus which is less virulent whereby the host and a phage can exist together for many years), enterobacteria T2, and T4 phages (lytic viruses which infect the bacteria known as *Escherichia coli)*. Likewise, there are insect viruses which affect insects only, and these include; Baculovirus, Sacbrood virus, Entomopox virus and Granulosis virus.

Based on the type of disease they cause, viruses can be classified as; measles virus; cause measles, polio virus; cause polio, and rabies virus; cause rabies. According to morphology there are different categories based on the symmetry of capsid which include helical and icosahedral viruses, the helical morphology consists of helical array of capsid proteins wrapped around a helical filament of genetic material, example TMV, whereas in icosahedral the protein subunits are arranged in a form of hollow, quasi spherical structure, example; Herpes simplex virus.

3.2.2 General structure of viruses

Viruses are composed of fragments of genetic material (DNA or RNA), which forms a nucleic acid core. The DNA contains a few genes and can either be single or double stranded. The nucleic acid core is enclosed by a protein coat called capsid as in bacteriophage. The capsid is made up of small identical protein sub units called capsomeres which are structures that enable viruses to crystallize and assume a non-living matter. The capsid, together with the genetic material (DNA or RNA), constitute a nucleocapsid. Some viruses may have additional envelope of lipoprotein (lipid rich protein) around the capsid. The lipoprotein layer is usually derived from the cell membrane of the host cell. The viruses with this layer are called enveloped viruses, examples are influenza and herpes viruses. Those with no envelope are referred to as naked viruses, for instance, bacteriophage or simply a phage; viruses that attack bacteria (Figure 3.1 a, b and c).

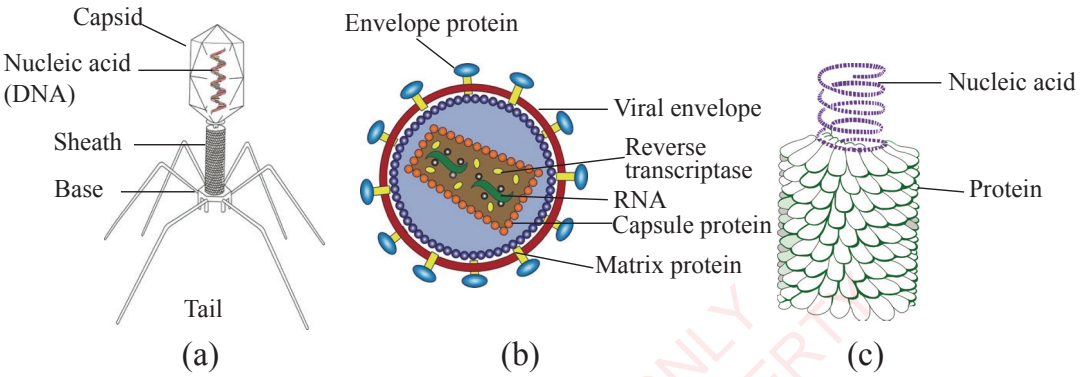


Figure 3.1 Structure of (a) Bacteriophage (b) the Human Immunodeficiency Virus (HIV) and (c) Tobacco mosaic virus (TMV)

3.2.3 Viral replication

Viral replication involves formation of viruses during the infection process, and they replicate only when in living cells; that is the viruses must first get into the host cell before viral replication can occur. Replication between viruses differ significantly and depends on the type of genes in them. For example, most DNA viruses gather in the nucleus while most RNA viruses develop merely in the cytoplasm.

The life cycle of a bacteriophage

In principle, viral life cycle is the same in all bacteriophages. Retroviruses such as Human Immunodeficiency Viruses (HIV) show uniqueness at a certain stage of their replication due to ability to convert their RNA back into a DNA copy. Some viruses called *lytic phages* kill host cells immediately after they enter. On the other hand, other viruses such as lambda phages may remain dormant for a long time after inserting their DNA into the host DNA, but they may eventually be activated to complete their life cycle. These types of viruses are described as lysogenic phage and the dormant stage is called prophage. The viral replication therefore, occurs in two major stages or phases, namely; lysogenic and lytic phases or cycles as summarised in Figure 3.2, and Figure 3.3 respectively.

a) Lysogenic cycle

When a phage contacts a bacterium, its tail fibers attach to receptor sites on the bacteria and it sheds its protein coat outside the host cell. The viral DNA is incorporated in the bacteria chromosomes (simple circles of DNA) and is replicated along with it. Therefore, replicated copies of viral DNA will be produced each time the bacteria cell divides. However, the phage is not virulent at this stage but dormant, and bacterial cells may exist together with the dormant phage DNA for many generations. This dormant or latent stage of the phage is also termed as prophage and the host's cell as a lysogenic cell. The viral DNA released may enter a virulent pathway called lytic cycle, if activated (Figure 3.2).

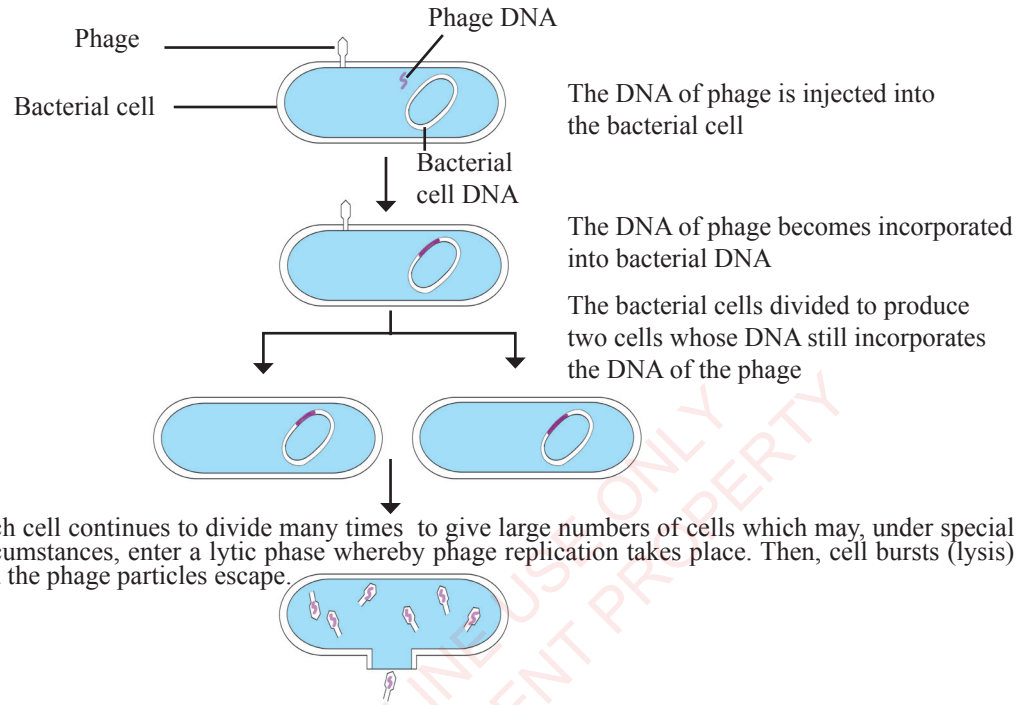


Figure 3.2 The life cycle of a lysogenic phage

b) Lytic cycle

When a phage particle approaches the host cell, it attaches to the host wall and injects its genetic material. Other lysogenic viruses may be activated to enter the lytic cycle; this occurs when their genetic materials are already inside the host cell. They undergo replication and produce more phages, disrupting the host's DNA as a result, the phage DNA takes control of the bacterial cell machinery, replicates more repeatedly, and codes for its new coat proteins. New viral proteins and new virus particles are assembled. As a large number of new viral particles is produced, the phage also produces lysozymes containing digestive enzymes which digest the host cell. This makes the host cell to burst and release phages. Due to the digestion of the host cell caused by the phage, this phase is

termed as lytic phase from the word lysis meaning 'digest'. The host cell lysis and release of phages mark the culmination of the lytic phase (Figure 3.3). The newly produced phages are capable of infecting a new bacteria and the cycle starts over again as lysogenic cycle with or without a break or dormant stage.

The lysogenic and lytic cycles can be distinguished due to the fact that, in lysogenic cycles, the spread of the viral DNA occurs through the usual bacteria reproduction as their DNA has incorporated with the bacteria DNA while in a lytic cycle, the viral DNA and the host DNA replicate separately within the host cell resulting in many copies of the virus being produced very quickly. Also, the lysogenic cycle does not lyse the host cell straight away while in the lytic cycle, the host cell is lysed or destroyed.

Phages that replicate using both lytic and lysogenic cycles are called temperate phages while phages that replicate only through the lytic cycle are called virulent phages.

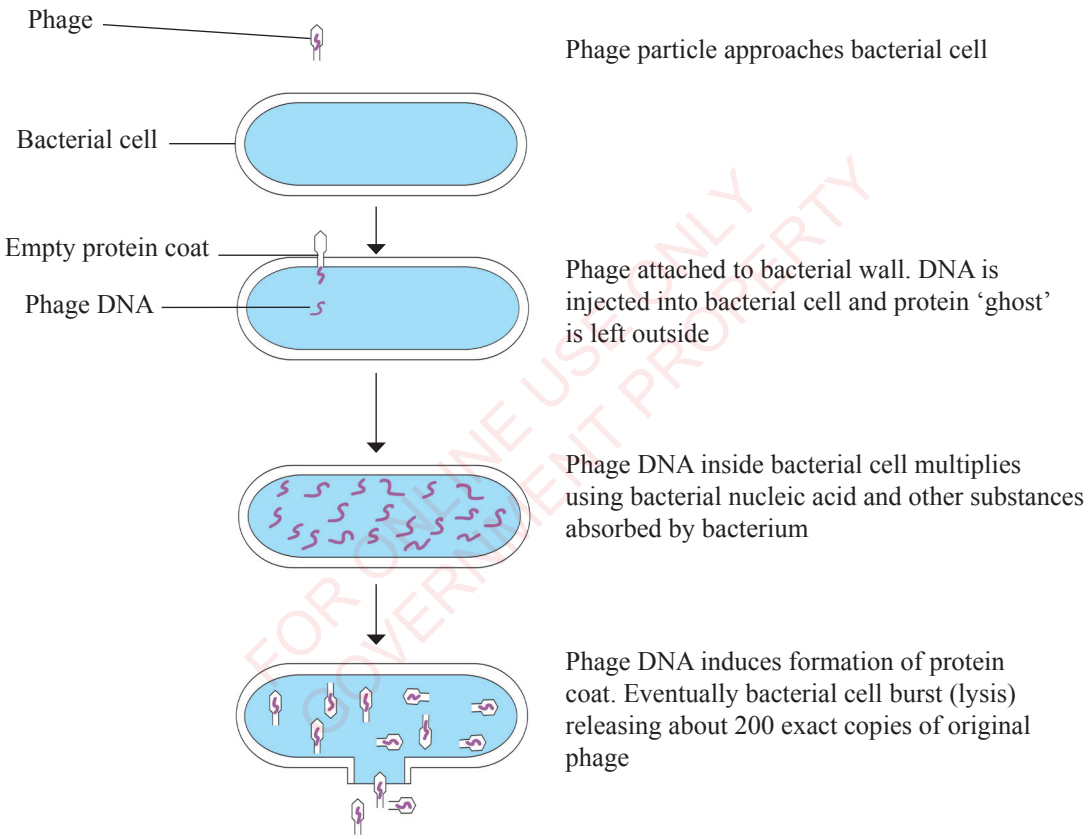


Figure 3.3 The life-cycle of a lytic (virulent) phage

Retroviruses

These are special groups of viruses that contain an enzyme named reverse transcriptase, which is capable of synthesizing a DNA copy from the virus RNA. This is unlike the usual transcription in which RNA is synthesized from a fragment of DNA. Literally, the term *retro* means 'reverse or going back.' Hence, retroviruses were so named due to their ability to undergo this reverse transcription process in producing DNA copies from RNA. These copies can be incorporated randomly into chromosomes of the host DNA. It is in this group where the Human Immunodeficiency Virus (HIV), Hepatitis B viruses and Herpes viruses belong. The retrovirus DNA is known as provirus. Provirus can be injected in the host DNA and remain dormant for a long time prior to expression and formation of its new RNA. At this stage, the host does not portray any sign of infection. This explains why it sometimes takes a long time for people infected with HIV to develop AIDS symptoms. However, when provirus is incorporated into the host cell DNA, it may activate host genes to produce RNA which will be packaged inside the retrovirus particles and delivered together with retroviral RNA to the next infected cell. The retrovirus binds on T-helper lymphocytes and destroys them and cripples the immune system.

3.2.4 Economic importance of viruses

Though viruses have some disadvantages; as they cause diseases to organisms by being endoparasites and infectious pathogens, yet some have significant beneficial in medical industry, biotechnology, research, agriculture and ecology. Furthermore, viruses have been used as biological warfare (biological weapons) and cause devastating epidemics in human societies, as they are highly infectious and relatively easy to produce.

Advantages of viruses

a) Viruses are widely applied in preparation of vaccines against animal diseases. Currently, there is a number of vaccines against deadly human diseases such as poliomyelitis, measles, and yellow fever.

b) Viruses such as bacteriophages play a great role in marine ecology and carbon cycling.

c) Viruses are important in the field of molecular and cell biology; they help in manipulating and investigation of cells, hence providing valuable information about the aspects of cell biology.

d) Some viruses are used in biological studies. Example, the enzymes reverse transcriptase discovered in retroviruses are currently widely used in various aspects in genetic engineering.

e) They stimulate the synthesis and release of interferon in the body. This suppresses the viral replication and stimulates the activity of cytotoxic cells.

f) They are used in gene therapy through genetic manipulation of somatic cells of individuals as well as in production of transgenic plants and animals.

g) Certain pathogenic viruses can be used as a pests control agent.

Disadvantages of viruses

a) Viruses are known to cause various diseases in living organisms, for example influenza, measles, ebola, AIDS, chickenpox, and herpes in

human, potato mosaic and tobacco mosaic in plants, and newcastle in poultry.

b) Some viruses can cause chronic infections; for example, the virus can replicate the entire life of the host, regardless of the presence of the host's defense mechanisms. This is common in Hepatitis viral infection and in HIV.

c) A host with chronic viral infections can be a carrier of an infectious virus for lifetime. It can sometimes kill many cells, causing the organism to suffer ill effects.

Exercise 3.1

1. With examples, explain when and why viruses are considered to be a living and non-living organism.
2. Describe the life cycle of a bacteriophage, showing the main events of viral replication.
3. Briefly explain why vaccines against many viral diseases are currently available but HIV vaccination is still a challenge to medical biologists.
4. Giving reasons, briefly explain in which phase of the life cycle does HIV replication occur.

3.3 Kingdom Monera

The kingdom Monera consists of unicellular prokaryotes. Literally, the term prokaryote is a combination of two Greek words, *pro* meaning 'before' and *karyo* meaning 'nucleus,' which simply means before nucleus or without a true nucleus. Although prokaryotes have no true nucleus, they still have diffuse area(s) of nucleoplasm called nucleoid, containing genetic materials with no distinct nuclear membrane or envelope. This is a very unique feature unifying all prokaryotes. It makes them distinct from species of the other four kingdoms which have membrane enclosed nuclei. Lack of membrane bounded nucleus makes prokaryotic organisms evolutionarily the most primitive life forms. It is believed that the oldest prokaryote evolved about 3.5 billion years ago. Moreover, most organisms under this kingdom have a cell wall containing peptidoglycan (Refer to Figure 1.3).

Prokaryotic organisms are diverse, and they constitute the largest group interms of abundance of organisms it encompasses. Studies show that a gram of soil may contain approximately 2.5 billion bacteria, while a cubic centimeter of milk has more than 3,000 million bacteria. Organisms belonging to this kingdom are very minute (1- 10 µm) to be seen without the aid of a microscope and are thus termed as microscopic. This is the reason why kingdom Monera was not among the two traditional kingdoms; Plantae and Animalia, as it was still difficult to see, identify, and characterise them. The discovery of the Monerans, therefore, came following the discovery of the microscope, particularly the electron microscope and computer applications which revealed the finer details of the Monerans. This simplified the understanding of differences across members of this kingdom, leading to the recognition of the three major divisions, namely; division Archaea, Eubacteria, and Cyanobacteria. Earlier classification

system splited Monera into two groups, in this case, all Archaea bacteria were grouped under kingdom Archaebacteria while Cyanobacteria and Eubacteria were classified under kingdom Eubacteria or Prokaryota.

The members of kingdom Monera are cosmopolitan in distribution and predominant in all habitats, ranging from aquatic; that is marine, brackish and fresh waters to terrestrial environments; such as in the air, dust, soils, on plants and animals. They also range from parasitic, free living and symbiotic bacteria to animals and plants. Some bacteria are saprophytes, especially decomposers, which are very important in nutrient cycling. Nitrogen fixing bacteria are found in symbiotic association with leguminous plant roots while the cyanobacteria form symbiotic relationships called lichens with fungi. Parasitic prokaryotes include infectious bacteria such as *Salmonella typhi* that causes typhoid and *Vibrio cholerae* which causes cholera, spend part or their entire life in their hosts as facultative parasites or obligate parasites respectively. The free living bacteria are capable of synthesizing their own food using energy obtained from light or chemicals. The former is called photoautotrophic bacteria such as Purple sulphur bacteria, while the latter is called chemoautotrophic bacteria such as Iron bacteria (*Ferrobacillus*). Some prokaryotes such as Archaebacteria have interesting features such as the ability to survive in extremely harsh environments, such as very low oxygen concentration (anoxic condition), high alkaline or acidic media, high salt concentration, and extreme temperatures (in hot springs and volcanic domes) where other organism have completely failed to inhabit. For example, methanogens (*Methanobrevibacter ruminantium*) which produce methane gas in anoxic conditions in ruminant's digestive systems. These similar bacteria produce methane gas from cow dung which is used as biogas, which is one of the renewable sources of energy.

3.3.1 Characteristics of monerans

a) They are very microscopic unicellular organisms, with an average diameter of 0.1-10 μm.

b) Their cells lack a well organised nucleus, since they have no nuclear membrane, and the nuclear materials are freely suspended in the cytoplasm.

c) They lack cytoskeletons and membrane bound organelles, such as mitochondria, plastids, and chloroplast. The photosynthetic Moneras have photosynthetic lamella instead of chloroplasts.

d) They have few and smaller ribosomes, 70s ribosomes.

e) They have small, circular DNA that lacks the histone protein coat.

f) Most of physiological processes, such as respiration and food synthesis (for the autotrophs), occur in membrane systems.

g) The cell wall is composed of a carbohydrate-protein complex called murein or peptidoglycan.

h) Most prokaryotes move using a beating flagella, gas vesicles, and gliding mechanisms. Flagella, if present, lack an internal 9+2 fibril arrangement pattern.

i) They reproduce asexually by binary fission and sexually by conjugation, no mitotic and meiotic divisions, hence no spindle formation.

3.3.2 Classification of Monera

The microorganisms in kingdom Monera are considered as primitive organisms and the most ancient living forms on earth. This kingdom is divided into two main groups which are Archaebacteria (Extremophiles) and Eubacteria (cyanobacteria and true bacteria). In this text, much emphasize will be devoted to Eubacteria.

Division Archaebacteria

Under this group, bacteria are the most primitive and ancient members of kingdom Monera. Their cell wall chemistry differs from eubacteria as they lack peptidoglycan. Instead, they have lipids which are different in composition from other bacteria due to the presence of long chains of fatty acids with glycerol attached to it by ester linkage. Another unique feature of these bacteria is their ability to inhabit extreme environments in which other organisms cannot survive. These habitats include environments with extreme temperatures, saline, and acidic conditions. Others can survive in oxygen deprived or anoxic conditions. Because of their ability to survive in extreme conditions, Archaebacteria are grouped into methanogens, which produce methane by reducing carbon-dioxide, for example, methanogens *(Methanobrevibacter ruminantium)* found in ruminants' digestive system. The other group is hyperthermophiles which are temperature-loving and acid-loving archaeans (acidophils). They are found in hot springs and acidic conditions such as in hot springs and phosphoric or arsenic ponds. The third group is the extremohalophiles which are salt loving archaeans found in salt lakes. Other classification systems treat Archaebacteria as a kingdom and place the groups of archaea into distinct phyla or divisions while the entire group of Archaebacteria in this text is regarded as a division.

Division Eubacteria

These include the true bacteria and the cyanobacteria, also known as blue-green bacteria or blue-green algae, which are photosynthetic. Members of this division lack true nuclei and they have a strong and rigid cell wall containing a polysaccharide called murein cross-linked by short chains of amino acids. They have a variety of shapes ranging from spherical, rod-like, and spiral or comma shaped. Additionally, some are heterotrophs, living as pathogenic parasites while others are free living autotrophs. Furthermore, eubacteria have simple circular DNA which is not associated with proteins to form chromosomes and they use mesosomes for respiration.

Cyanobacteria are grouped in the same division with other true bacteria, because they share many features. For example, both possess prokaryotic cell structures, reproduction by binary fission, their cell wall contains peptidoglycan (murein), and have mucilaginous sheet.

In other classification systems, cyanobacteria form a division of their own called Division Cyanobacteria. This is because, unlike bacteria, they have chlorophyll *a* for photosynthesis and they produce oxygen during photosynthesis which resembles algae more than bacteria. In addition, their chlorophyll lamellae and DNA lie free in the cytoplasm. Cyanophytes can occur as free living cells or as colonies. They have specialised cells called heterocyst which are capable of fixing Nitrogen. These bacteria form blooms in ponds. Sometimes, they are found in symbiotic association called lichen with fungi.

Classification of bacteria

Bacteria are single celled microbes, with a simple cell structure that has no nucleus or membrane bound organelles. Although genetic divergence specifies the evolutionary relationships of bacteria, reaction to Gram stain, mode of nutrition, morphological, motility, and biochemical features of bacteria remain important in the identification and classification of these organisms. Three major ways can be used to identify bacteria; based on their cell wall chemistry or composition which makes them respond differently to Gram stain, difference in morphology of their cells, and mode of nutrition.

Classification of bacteria based on their staining properties

In this case, the bacterial cell is smeared on a microscope slide and stained with crystal violet solution followed by iodine solution, and later washed with organic solvent such as acetone or ethanol and counterstained with a red dye called safranin or carbolfuschin. This staining based classification of bacteria was invented by Hans Christian Gram, a Danish microbiologist in 1884, and was therefore named "Gram stain's test." This simple test classifies bacteria into two broad groups namely; Gram negative and Gram-positive (3.4 a and b). The Gram-positive bacteria appear blue to purple, because they retain the crystal violet colour of the dye used to stain them. In contrast, the Gram-negative bacteria do not retain the colour of the stain (crystal violet).

The staining differences are based on variation in the cell wall chemistry, particularly in the amount of peptidoglycan. The Gram-positive bacteria have a simple cell wall with a thick layer of peptidoglycan (polysaccharides and protein). Moreover, due to differences in cell wall constituents, the Gram-positive bacteria cell wall is susceptible to lysozymes and antibiotics. The Gram-negative bacteria are resistant to antibiotics and lysosomes. This is because, although they have thinner cell walls, they are more complex, by having additional outer layer on the outside of murein layer which is thin, smooth membrane-like containing lipid and polysaccharides that protect the bacteria from host's lysozyme, as well as antibacterial enzymes found in tears, saliva and other body fluids. Examples of Gram-positive bacteria include *Bacillus* sp., *Clostridium* sp., *Streptococcus* sp., and *Staphylococcus* sp., while Gram-negative bacteria include *Escherichia coli, Chlamydia* sp., *Neisseria* sp., *Salmonella* sp., *Treponema* sp., and *Azotobacter* sp (Figure 3.4).

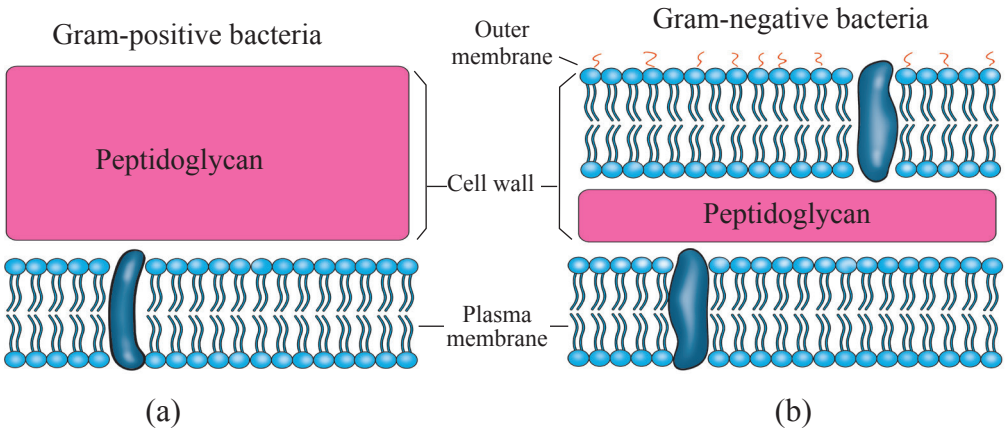


Figure 3.4 Structure of a bacterial cell wall (a) Gram-positive and (b) Gram-negative bacteria

The framework of the protein that makes the peptidoglycan materials of the cell wall is a porous network that allows diffusion of the staining solution (see the three dimensional detailed view of the Gram-positive bacteria in Figure 3.5).

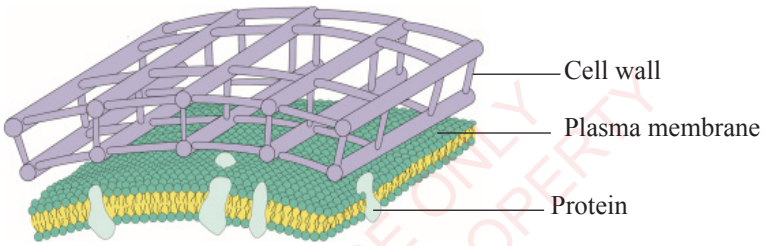


Figure 3.5 Structure of a bacterial cell wall (detailed view of the cell wall)

Activity 3.1 Identification of Gram-positive and Gram-negative bacteria

Materials

Dried smears of bacteria, gentian violet or iodine solution stain, alcohol, red dye (safranin/ carbolfuschin), and watch glass.

Procedure

a) Place an air dried smear on a watch glass.

b) Gently flood the smear with iodine solution or gentian violet, and let it stand for one minute.

c) Decolourise by adding alcohol, drop by drop until no further stains come out.

d) Counterstain by flooding the smear with a red dye such as safranin or carbolfuschin and let it stand for about 40-45 seconds.

e) Observe the colour change and explain your results.

Classification of bacteria based on their morphology

Bacteria can be classified according to their morphology or shapes, which are diverse, ranging from rod-like to comma-like shapes. They can exist singly or in a series of interconnected individual cells called colonies. This should not be confused with multicellular organisms, because each cell is capable of carrying out all its essential life processes, and each can survive independently if separated from the colony. The cells normally associate to form a colony after binary fission, as the two resulting cells adhere to each other. Some bacteria cells associate in tubular sheaths, forming filaments which undergo binary fission simultaneously. Four shapes of bacteria exist, namely cocci, bacilli, spirilla, and vibrio or comma-shape.

Cocci (singular coccus)

These are spherical-shaped bacteria. They may exist as a single cell, while others may exist in pairs, forming a double-celled (diplococcus) organism. The diplococus may be surrounded by a capsule, for example the pneumococcus bacteria (*Diplococcus pneumoniae*) a causative agent of pneumonia. They may also occur in chains of interconnected individuals or in bunches (cluster cells) such as *Streptococcus* and *Staphylococcus* respectively (Figure 3.6 a, b, c, and d).

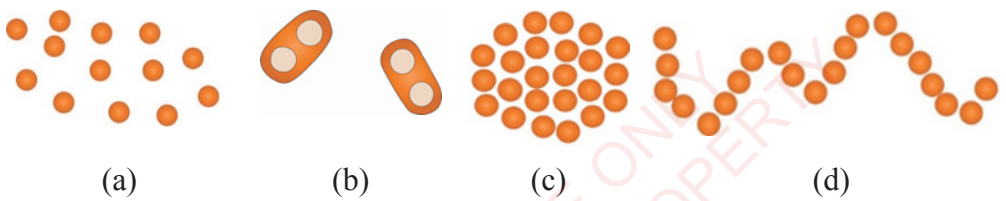


Figure 3.6 Structures of cocci bacteria (a) single-celled (b) double-celled (c) colon and (d) chain

Bacilli (singular bacillus)

These are rod-shaped bacteria which may occur singly as in *Escherichia coli; a* common gut-living symbiont and *Salmonella typhi* which causes typhoid fever. The bacilli may occur in chains as seen in Nitrogen fixing bacteria (*Azotobacter*) and the anthrax causing bacteria (*Bacillus anthracis*). The bacilli usually have a tendency of forming endospores with various shapes, position and size, examples include oval spore without swelling at the center like in *Bacillus anthracis*, and spherical spore with a swollen terminal like in *Clostridium tetani*; the causative of tetanus or with sub-terminal swollen example *Clostridium botulinum* the causative of botulism (Figure 3.7 a, b and c).

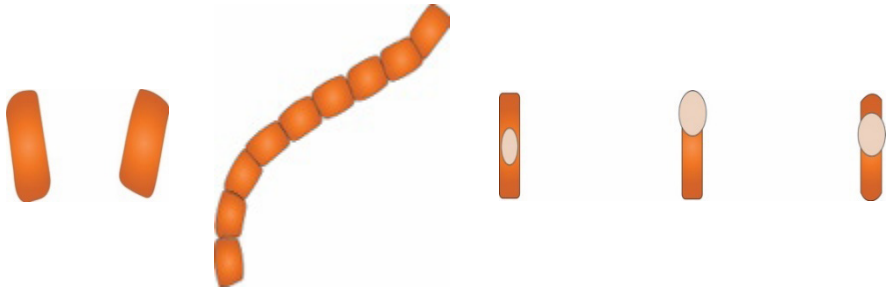


Figure 3.7 The structure of bacilli bacteria (a) single rods (b) chained rod and (c) *Bacilli* with endospores

Spirilla (singular spirillum)

Bacteria in this group have a long cylinder cell, coiled into a spiral or helical body. The individuals under this group are also called spirochaetes; their name came from the fact that they contain distinctive double membrane, and most of which have long helically coiled structure (corkscrew-shaped or spiraled). They are also characterised by presence of unique axial filaments composed of flagella, running from one end of the cell, where they are directly attached to the cell wall. The flagella are used for locomotion. Bacteria under this group include free living bacteria found in water and muds as well as parasitic spirochaetes such as *Treponema pallidum* that causes syphilis in humans **(**Figure 3.8**).**

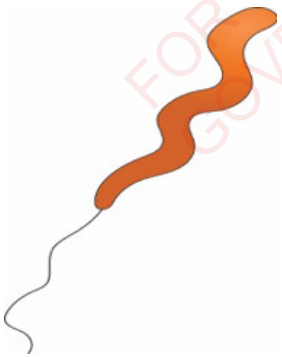


Figure 3.8 The structure of a *Spirillum* bacterium

Vibrio

This group of bacteria includes various curved bacteria which appear superficially like a comma. That is why they are sometimes named as comma-shaped bacteria. These bacteria possess a single flagellum which is used in locomotion as seen in *Vibrio cholerae* (Figure 3.9).

Figure 3.9 The structure of a comma-shaped bacterium

Classification of bacteria based on their mode of nutrition

Bacteria obtain their food from their environment in different ways. Some of them can synthesise their own food using energy from the sunlight, while others use chemicals as their energy source. Some of the bacteria cannot synthesize their own food and they rely on other organisms as their source of food. Thus, in this regard, bacteria are classified into

photoautotrophs, chemoautotrophs, and chemoheterotrophs.

Photoautotrophs

Photoautotrophs bacteria need light as their source of energy in manufacturing their food. The light is trapped with the aid of chlorophyll *'a'* and carotenoid pigments. This type of photosynthesis is much simplified compared to that of plants. Examples include blue-green bacteria.

Chemoautotrophs

These bacteria acquire their energy by oxidising simple inorganic substances, but not from sunlight as in photoautotrophs. The obtained energy is used to synthesise food in the presence of carbon dioxide. Important nitrogen fixing bacteria such as *Nitrosomonas* and *Nitrobacter* belong to this group. Others include Iron bacteria which oxidise Iron two (Ferrous Iron) to Iron three (Ferric Iron), and the energy released from oxidation is utilised during food synthesis.

Chemoheterotrophs

All bacteria which cannot manufacture food on their own as they lose the ability to photosynthesize in the course of evolution are heterotrophs (heterotrophic bacteria). They are named "chemo" heterotrophs, when they obtain energy for their growth from organic compounds such as proteins and glucose. Chemoheterotrophs can be further categorised into saprotrophs, parasites and mutualists. The saprotrophs obtain their food from dead and decaying organic matter, majority of them are decomposers, which are very important in nutrient recycling. Parasitic bacteria are pathogenic as they obtain their foods by living in or on other organisms thereby causing diseases and even death of their hosts. Some bacteria live permanently on or in their host (obligate parasitic bacteria), while other bacteria's life cycles depend on multiple host (facultative parasitic bacteria). Other bacteria live in a mutual (symbiotic) relationship with other organisms where by both partners benefit from the association. Examples of symbiotic association include; *Rhizobium* bacteria that live in the root nodules of leguminous plants, and also have ability to fix nitrogen into useful compounds like nitrates which are needed by these plants, and *Escherichia coli* which live symbiotically in the human gut and contribute to the formation of vitamin B and K.

3.3.3 Bacterial reproduction

Bacteria reproduce both sexually and asexually; sexual reproduction involves two organisms/cells exchanging their genetic materials (not gametes, as they have no reproductive structures) and produce daughter cells which differ in their genetic materials from that of the parental cells. Sexual reproduction involves the process of genetic recombination through cell to cell contact (Conjugation), while in asexual reproduction the cell divides by binary fission to form two daughter cells with similar genetic materials as that of the parental cell.

Asexual reproduction in bacteria

Most bacteria reproduce asexually. A single bacterium can reproduce asexually by binary fission which involves division of one bacterium into two bacteria (Figure

3.10). In this process, the dividing cell elongates and if the cell is spherical, the elongation is very much restricted. A rod-shaped bacterium elongates to almost double its size. Then, the protoplasmic mass divides into two equal halves by a transverse wall or constriction. The cell division is preceded by the replication of DNA. The two daughter cells soon grow to maturity and divide further.

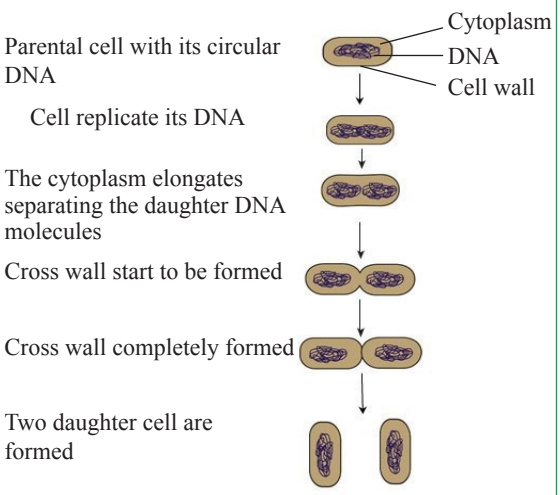


Figure 3.10 Bacterial reproduction by binary fission

Sexual reproduction in bacteria

Sexual reproduction in bacteria is primitive in the sense that it does not involve union of gametes as commonly seen in other organisms, particularly the eukaryotes. The reproduction simply involves combination of genetic material by the process called genetic recombination. This process involves the primitive form of sexual reproduction called conjugation (the transfer of DNA between two cells which are in direct contact). One of the two cells (male) donates while the other (female) receives genetic material. The ability to donate the genetic material is controlled by the bacterial gene found in a special type of plasmid called sex factor which also codes for the formation of a small tubular structure called pilus, connecting the two bacterial cells. Through this pilus, the genetic material is injected to one or more recipient(s) at a time. This kind of exchange is essential especially during unfavorable condition, and they produce more resistant cells (Figure 3.11).

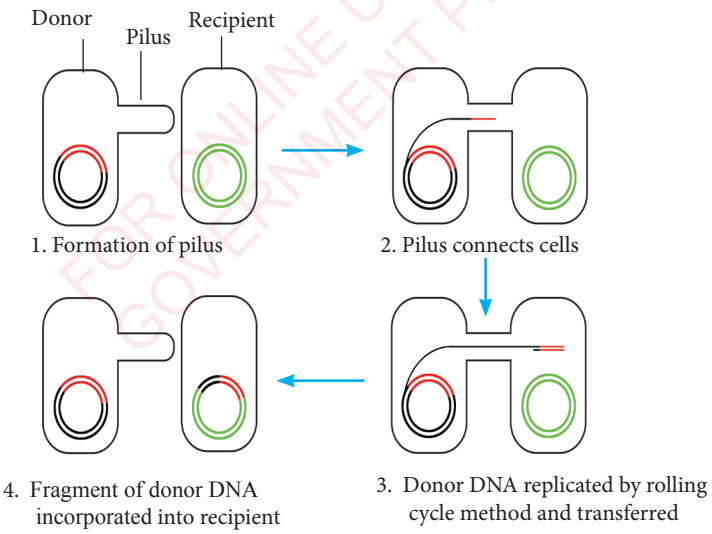


Figure 3.11 Sexual reproductions in bacteria

3.3.4 Economic importance of monerans

Bacteria have a wide range of economic importance; ranging from beneficial to detrimental effects to humans and other organisms. Furthermore, many bacteria serve important roles in both industries and agriculture.

Advantages of monerans

a) Production of vinegar

Some bacteria, such as those of genera *Acetomonas* and *Acetobacter* are used in making vinegar (for vinegar fermentation), whereby ethanol is partially oxidised into ethanoic acid (vinegar).

b) Manufacturing of dairy products

In this case, bacteria such as *Streptococcus lactis* are employed in preparation and preservation of commercial butter, cultured milk, and cheese from cream milk. The bacteria species *Streptococcus thermophilus* and *Lactobacillus bulgaricus* are frequently used in preparation of yoghurt by inoculating fresh milk with a starter culture containing *Brevibacterium linens* in order to produce the appealing smell in cheese.

c) Manufacturing of amino acids, proteins, and starch

In the manufacture of amino acids, some bacteria such as *Monococcus glutamis* are used. Industrial proteins such as amylase are produced by bacteria such as *Bacillus polymysa*.

d) Decomposition of organic matters

Most bacteria are chemoheterotrophs which obtain their food from dead or decaying organic matter. In so doing, such bacteria reduce heaps of dead substrates such as leaf litter, dead logs and animals into simple substances like nutrients which can be easily absorbed by other plants. This process is called decomposition and it ensures nutrients recycling. It is vital to nature because it unlocks nutrients locked in dead bodies of other organisms and makes them available to others.

e) Treatment and purification of waste water or sewage

Bacteria can be used in treating and purification of water or sewage in oxidation pond, by reducing the bulky of wastes and converting them into simpler forms which can be easily handled in the subsequent stages in a stabilisation ponds (lagoon). Examples of decomposers include *Streptomyces* sp. and *Bacillus* sp.

f) Making flavour, aroma and curing of agricultural products

Bacteria are used for production of different dairy flavour compounds, such as butyric acid, lactic acid and diacetyl in mixed cultures of *Lactobacillus acidophilus* and *Pediococcus pentosaceus.* Some bacteria such as *Bacillus subtilis* have been used to bring about several physio-chemicals and sensory changes in soybean foods to make it highly digestible and nutritious. *Bacillus subtilis* which dominate traditionally fermented soy foods have typical taste, texture and aroma which is popular in Asian and African countries. Certain bacteria such as *Bacillus megaterium* can be used in curing off the bitterness in leaves of tea and tobacco.

g) Nitrogen fixation and nitrification in the soil

Some bacteria, besides being decomposers are important in fixing atmospheric nitrogen into a form that can be utilised by plants by the process known as nitrogen fixation. Examples of nitrogen fixing bacteria are *Azotobacter, Clostridium,* and *Rhizobium*. Some bacteria convert ammonia into nitrates in the soil by the process known as nitrification. *Nitrosomonas* convert ammonia into nitrite which later gets oxidised to nitrates by *Nitrobacter*. The two processes are important in agriculture, because nitrogen is one of the elements required by plants in large quantity for growth and other physiological processes. Nitrogen contributes largely in improving agricultural yields.

h) Bioindicator in detecting water pollution

Cyanobacteria blooms in ponds can be used as bioindicator, since they are sensitive to water pollution. Changes in abundance of cyanobacteria in aquatic ecosystems can serve as indicators of water pollution.

i) Biotechnology and genetic engineering

Bacteria can be used to alter and replicate genes that are then introduced into plant or animals. Bacterial systems lend themselves to genetic manipulation in part because of their rapid reproduction rates. *Thermus aquaticus* (Taq) is a thermal stable bacterium which is used to produce DNA polymerase. DNA polymerase enzyme is used in amplification of short segments of DNA through polymerase chain reaction (PCR). Some genetically engineered bacteria of genus *Pseudomonas* are used in cleaning oil-contaminated water as they feed on oil spills.

j) Biodiversity studies

Bacteria may be one of the most abundant and species-rich groups of organisms, that mediate many critical ecosystem processes. They contribute significantly to the global biodiversity, given the existence of numerous species of bacteria. The position and role of each species in the ecosystem cannot be underrated. Cyanobacteria initiated early life on land as they were the first organism to produce oxygen from photosynthesis. Such oxygen was used by early aerobic organisms.

k) Medical application

Some bacteria such as *Streptococcus* are used in the process of manufacturing antibiotics, such as Streptomycin. *Streptococcus lactis* ferments milk to produce lactic acid which prevents growth of harmful bacteria in the stomach, by maintaining the acidic environment in the stomach. Lactic acid prevents bacterial vaginosis, thus preventing urinary tract infection (UTI). Starch, in the form of amylose, is produced for industrial uses by bacteria. For example *Escherichia coli* or *E. coli* are used in the mass production of asparaginase enzyme which has also a medical application in chemotherapy against lymphoblastic leukemia.

l) Symbiotic association with other organisms

Some bacteria such as cyanobacteria live in association with fungi in which the former synthesise food through photosynthesis

and supply it to fungi, while fungi provide support and protection from dehydration to cyanobacteria. Some non-pathogenic bacteria live on human skin and are important in destroying the bad bacteria that live in symbiotic association with human. For example, *Staphylococcus* is among skin microbiota (skin flora) that live symbiotically with human skin, protecting the host from pathogenic bacteria.In addition, *Ruminococcus* bacteria that live symbiotically with ruminant animals, breakdown the plant fibres (cellulose) into monosaccharides, and *E.coli* in human intestines synthesises vitamin K.

m) Biological control

Bacteria are potentially used in several biological control methods in agriculture and public health programs as bio pesticides. For example, some bacteria are soil dwelling Gram-positive, commonly used as biological pesticides. They infect and kill the destructive organisms, including caterpillar of some butterflies and larvae of some insects. An example of a soil dwelling Gram-positive bacterium is *Bacillus thuringiensis*.

Disadvantages of monerans

a) Pathogenic bacteria cause diseases in humans. For instance; *Vibrio cholerae* cause cholera, *Treponema pallidum;* syphilis, *Shigella dysenteriae*; shigellosis, *Salmonella typhi;* typhoid fever, *Entamoeba histolytica*; dysentery, *Mycobacterium tuberculosis;* tuberculosis, and *Escherichia coli* cause urinary tract infection (UTI).

b) In farm animals, some diseases such as anthrax in cattle, avian tuberculosis in poultry, and black leg in sheep, goat and cattle are caused by bacteria including *Bacillus anthracis*, *Mycobacterium avium,* and *Clostridium chauvoel* respectively.

c) Some bacteria cause diseases in plants, resulting into crop destruction, for example; corky root in lettuce, halo blight in beans, and bacterial pith necrosis in tomatoes are caused by bacteria such as *Rhizomonas suberifaciens*, *Pseudomonas syringae Pv. Phaseolicola*, and *Pseudomonas corrugate* respectively.

d) Foods with high protein content are often decomposed by bacteria leading into food spoilage. For example, the smell coming from rotten eggs or any other protein-containing foods results from decomposition of protein by proteolytic bacteria.

e) During the process of bioleaching, some bacteria such as *Thiobacillus* oxidise sulphides to form sulphuric acid and Hydrogen ions (H^+) which can leak into the ground and turn surface and ground water into acidic, hence water pollution; which is an environmental destruction.

f) Bacteria called *Clostridium botulinum* can release toxin in imperfectly canned food.

Exercise 3.2

1. Briefly explain why the Carolus Linnaeus classification system was silent about kingdom Monera.
2. Describe the general and distinctive features of division Eubacteria.
3. Citing the significance of each, explain two ways by which bacteria reproduce.
4. Give any four reasons to justify the placement of cyanobacteria under division Eubacteria.
5. Why some taxonomists separate Cyanophytes from division Eubacteria and place them in division Cyanobacteria.
6. Using relevant examples, explain the ways in which bacteria are ecologically and economically important.
7. Explain with examples, why bacteria are said to be successful colonisers.

3.4 Kingdom Protoctista

In the early classification of living organisms into four kingdoms, all organisms which could not fit into kingdoms Fungi, Plantae and Animalia were placed under kingdom Protista. This made kingdom Protista very diverse, as it accommodated both unicellular prokaryotes and eukaryotes. Later, with the use of molecular taxonomy, prokaryotes were separated from Protista to form a group of unicellular organisms lacking a well organised nucleus. These were placed under kingdom Monera, while all single-celled eukaryotes constituted kingdom Protoctista.

Recent phylogenetic studies have shown that even Protoctista is no longer a group of naturally related organisms. This makes it difficult to clearly define kingdom Protoctista. For example, protoctists such as algae have chloroplasts; hence, they are photoautotrophs. Amoeba is a heterotroph, while slime molds and water molds are saprophytes sharing many features in common with fungi than with other protoctists. It is for this reason, kingdom Protoctista is deemed controversial by contemporary taxonomists. This is why the classification system has advanced from five to eight kingdoms. Members under kingdom Protoctista have been separated into two kingdoms, namely Protozoa and Chromista. More recently, they have been separated into three kingdoms: Protozoa, Chromista, and Archezoa. However, this text will focus on Protoctista as a kingdom for convenience.

Protoctists can be defined as unicellular eukaryotic organisms other than fungi, plants, and animals. Evolutionarily, members in high kingdoms such as Fungi, Plantae and Animalia, have their ancestors in the Protoctista kingdom. Therefore, protoctists are eukaryotes consisting of unicellular and multicellular members. The multicellular protoctists consist of an assembly of similar cells such as *Spirogyra.* The major difference between protists and protoctists is that the former consists of only unicellular microscopic organisms (protozoans) while the later is the mixture of unicellular and multicellular organisms. Studies based on the base sequence of

mitochondrial and chloroplast DNA indicate that members of kingdoms Fungi, Plantae and Animalia have their ancestors in the kingdom Protoctista.

Characteristics of protoctists

a) Organisms under this kingdom are nucleated; that is, all are eukaryotes.
b) Some protoctists are unicellular while others are multicellular.
c) They lack tissue differentiation.
d) Protoctists are adapted to both, aquatic and terrestrial habitats.
e) They have various types of vesicles that perform different functions. These include their increased surface area to facilitate exchange of materials needed for their survival. For instance, contractile vacuole helps protoctists to discharge excess water taken by osmosis. They also have food vacuole, as in *Paramecium,* which helps them in digestion of engulfed food particles.
f) Their cell surfaces are diverse, ranging from just a plasma membrane as in Amoeba, to a stiffer surface as in *Euglena* to ensure the integrity of the cell.
g) Many protoctists are involved in endo-symbiotic relationship with other organisms. A good example is a radiolarian which harbors other photosynthetic protoctists. These protoctists, through photosynthesis, synthesise food that is shared by both, while the radiolarian in turn confers protection and provide some metabolites to the other symbiont.
h) Both asexual and sexual types of reproduction are common in the majority of protoctists, although some members lack sexual reproduction. Asexual reproduction occurs by binary fission (in which one nucleus divides), multiple fission (in which many nuclei divides into multiple daughter cells), or budding (in which a new cell grows on the surface of the mother cell). During all these types of asexual reproduction, an organism replicates its nucleus and divides to form new organisms. Sexual reproduction in protoctists is still primitive, given that it is mainly a recombination of genetic material.
i) Some protoctists are parasites, while others are free living organisms. The free living members are either autotrophs (such as *Spirogyra*) or heterotrophs (such as *Amoeba proteus*).

Classification of protoctists

Classifying protoctists has been a difficult task due to their high diversity. Traditionally, protoctists were subdivided into several groups based on their physical similarities to higher kingdoms of Animals, Plants and Fungi. This text will deal with six selected phyla of Protoctista namely; Rhizopoda, Zoomastigina, Apicomplexa, Euglenophyta, Oomycota, and Chlorophyta.

Phylum Rhizopoda

Rhizopoda is a broad group of protozoan amoeboid organisms placed in kingdom Protoctista. The shape and organization of pseudopodia are among the main characteristics that are used to classify

members of phylum Rhizopoda. This phylum comprises of all forms of amoeba including parasitic and free living amoeba. Parasitic amoeba include *Entamoeba hystolytica* which feeds on cells of the human colon, and cause amoebic dysentery also (amoebiasis). The disease is characterised by abdominal pains, nausea, vomiting, erosion of blood vessels of the gut and diarrhoea containing blood.

General characteristics of phylum Rhizopoda

They are found in sea water, fresh water, and in the soil. They can also be found in a mud shallow pond and slow flowing streams containing plenty of decaying organic matter.

a) They are single-celled eukaryotes and their cells have no definite shape.

b) They are unicellular whose bodies are surrounded by membranes. Their cytoplasms have two distinct regions, the plasmasol (inner) and plasmagel (outer).

c) Most of them are free living, forming important links in the food chains. They feed on plant and animal materials. In contrast, others are parasitic or infectious to animals, including human being; some human pathogens such as *Entamoeba histolytica* cause amoebic dysentery.

d) They reproduce asexually by binary fission.

e) They move by using pseudopodia; hence, amoeba and other protoctists using this mode of locomotion are called pseudopods.

f) They possess contractile vacuole that carries out osmoregulation. Normally, fluids in the amoeba cell are relatively more concentrated which allow more water to flow to their body in response to osmotic gradient. Amoeba in turn pumps out this water using their contractile vacuole.

Distinctive features of phylum Rhizopoda

Members of the group Rhizopoda have the following features which distinguish them from the rest of the protoctists.

a) They have pseudopodia, which are used for both locomotion and feeding. Such pseudopodia are constantly changing as amoeba moves and feeds. Food particles and small organisms are engulfed using pseudopodia and digested in the food vacuoles. The digested food is assimilated into the rest of the body. This type of feeding is called phagocytosis. Ingestion is by endocytosis and egestion is by exocytosis.

b) The food vacuole and the oil droplets of amoeba confer a granular appearance to the endoplasm.

c) They possess a contractile vacuole, which carries out osmoregulation. When the contractile vacuole reaches a certain size, it fuses with the cell membrane where water is released outside the cell.

d) Their cytoplasm has two distinct regions; viscous outer layer ectoplasm (plasmagel) and more fluid internal endoplasm (plasmasol).

Structure of *Entamoeba histolytica*

Entamoeba histolytica has a regular body which changes constantly. The body is covered by a thin semi-permeable membrane called plasmallema or plasma membrane; and it is differentiated into two distinct portions; an outer ectoplasm (plasmagel) and an inner endoplasm (plasmasol). In the endoplasm, there is a prominent nucleus which is enclosed by a nuclear membrane. They possess pseudopodia for locomotion and feeding by engulfing food substances (Figure 3.12).

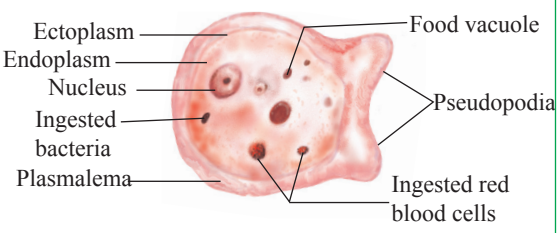


Figure 3.12 Structure of *Entamoeba histolytica*

Adaptations of *Entamoeba* to its mode of life

Some amoeba such as *Naegleria* are free living; they can live in different habitats such as on the bottom of ponds and lakes, whereas others like *Entamoeba* exhibit a parasitic mode of life. Parasitic amoeba have the following adaptations to their mode of life.

a) They can form cysts which resist digestive agents in the stomach.

b) They lack contractile vacuoles, since they live in isotonic state with the host's gut fluid.

c) They live where there is a plenty of food supply from their host.

d) They are physiologically tolerant to low oxygen concentration, since they live in areas with low oxygen supply in the large intestine.

e) They have rapid binary fission and production of a large number of cysts to ensure their existence and perpetuation in alternative hosts.

f) They can feed on various foods, ranging from bacteria to blood cells, and digest them with their enzymes.

Exercise 3.3

1. Give reasons as to why some taxonomists consider Protoctista as an obsolete kingdom.
2. Explain the reason why both Monera and Protoctists are single-celled organisms but belong into different kingdoms.
3. Describe any five features which make *Amoeba* a specialised form of protoctists.
4. What is the economic importance of *Entamoeba?*

Phylum Zoomastigina

This phylum consists of flagellated parasitic protoctists. It contains free-living organisms, some are symbionts, such as protozoans which live in the gut of termites and digest cellulose in the wood eaten by the termites, and some are parasites. Examples of parasitic organisms found in this phylum include *Trypanosoma gambiense;* a parasite causing African sleeping sickness.

General characteristics of phylum Zoomastigina

a) The phylum Zoomastigina contains organisms such as *Trichonympha* and *Trypanosoma*, which have one or two flagella.

b) The members of this phylum are heterotrophic; single-celled organisms.

c) It comprises of both free-living and parasitic organisms. Free-living Zoomastigina are found in ponds and puddles with plenty of organic matter while a few such as *Trypanosoma* are parasites.

d) Some have undulating membrane.

e) Most of them reproduce by a simple binary fission.

f) The body is overlaid by a semi-rigid pellicle.

Distinctive features of phylum Zoomastigina

Zoomastigina species differ from the other members of the kingdom Protoctista by being the only heterotrophic unicellular eukaryotes with one or more flagella.

Structure of *Trypanosoma*

The genus *Trypanosoma* contains a large number of parasitic species which infect wild animals, domesticated animals and humans. *Trypanosoma* is divided into several sub-genera based on morphological differences. Different species of trypanosomes are transmitted by insects. Examples include; *Trypanosoma cruzi, Trypanasoma brucei* and *Trypanosoma gambiense* which is a causative agent of sleeping sickness in humans. This parasite is common in west and central Africa, its vector is a tsetse fly, *Glossina palpalis*. It is about 15µm long, and 1µm wide, pointed at both ends and bears a prominent ovoid nucleus in the central region. It is enclosed in a strong pellicle which maintains the body shape. The entire body is covered by a wavy undulating membrane. Along the edge of the membrane is a flagellum attached posteriorly to a small granule known as a blepharoplast (basal body). Anteriorly, the flagellum projects in front of the body as a short, fine slash, and immediately posterior to the basal body, there is a prominent granule, a parabasal body (Figure. 3.13).

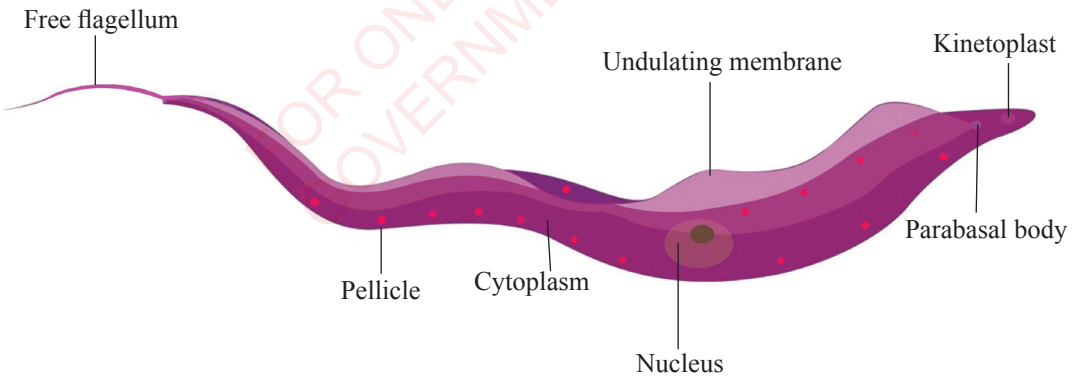


Figure 3.13 Structure of a *Trypanosoma*

Adaptations of *Trypanosoma* spp. to their mode of life

Trypanosoma spp. are highly adapted to parasitic mode of life in their hosts due to possession of the following adaptive features:

a) They have large surface areas to volume ratio. This is important for absorption of oxygen and food from their hosts.

b) They live isotonically within the blood plasma of their hosts. They lack contractile vacuoles and osmoregulation does not take place.

c) They have rapid reproductive rate by binary fission which ensures that large number of parasites are produced. Large number of these parasites is potentially important especially in adverse conditions where some parasite formed die, but some will remain.

d) They have a hard pellicle that protects cytoplasmic structures and restricts action of digestive agents of the host.

e) They are able to remain dormant in their host's cells of liver and spleen during adverse conditions. This ensures existence of the species.

Exercise 3.4

1. Explain the distinctive features of the phylum Zoomastigina.
2. Describe the structure of a *Trypanosoma*.
3. Normally, areas infested by tsetse flies are not suitable for human settlement. Justify.

Phylum Apicomplexa

This phylum consists of eukaryotic unicellular organisms, which are spore forming parasites of animals. They are also known as sporozoans; an example is the parasite *Plasmodium* which cause malaria in humans.

General characteristics of phylum Apicomplexa

a) Most of them possess a unique type of plastid called an apicoplast, used for piercing host cells.

b) They are unicellular and spore forming organisms. Almost all species are obligate endoparasites of animals, except nephromyces which live symbiotically in marine animals.

c) They have an infectious stage known as sporozoite.

d) They reproduce asexually by schizogony and sexually by sporogony.

e) The parasite changes its shape depending on the host it inhabits. For instance, it is sickle shaped in salivary glands of mosquito, while it is spherical or amoeboid in liver cells of humans.

f) They are non-motile.

g) They form resistant spores after fertilisation.

Distinctive features of phylum Apicomplexa

Organisms in the phylum Apicomplexa differ from other groups by the following features:

a) They have a plastid called apicoplast, which is used for piercing host cells.

b) They reproduce asexually by schizogony in the human body and

sexually by sporogony in the mosquito.

c) They change their shapes depending on the host it inhabits. For instance, plasmodium is sickle shaped in salivary glands of mosquito, while it is amoeboid in liver cells of human.

Structure of *Plasmodium*

The *Plasmodium* is oval shaped, and lacks contractile vacuoles and locomotory organs. The apical end is a bridged cone-shaped projection demarcated by the polar rings. A single mitochondrion is generally present at the posterior end and the Golgi apparatus is unremarkable. Just beneath the inner membrane, there is a row of microtubules which originate from the polar end of the apical end and continue to the posterior end. Attached to the nucleus, there is an endoplasmic reticulum, a network of membranous tubules within the cytoplasm (Figure 3.14). Additionally, there are the rhoptries, which are the specialized secretory organelles.

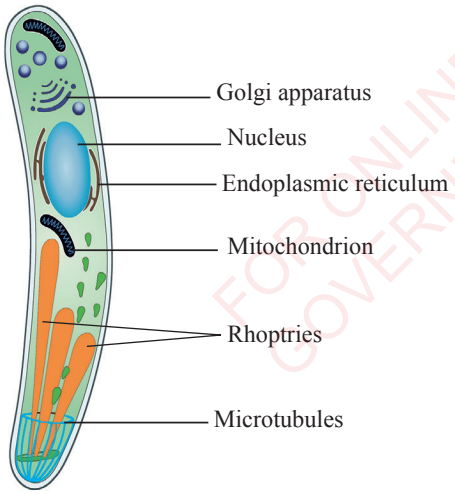


Figure 3.14 Structure of a *Plasmodium*

Life cycle of *Plasmodium*

The parasite in the form of sporozoites enters the blood stream of the human being after a mosquito bite. It then travels to the liver and invades it (Figure 3.15). The sporozoites grow, divide and produce many haploid forms called merozoites or schizozoites in liver cells. The merozoites in the liver cells exit and re-enter blood stream, where red blood cells are invaded. The merozoites multiply in the red blood cells by asexual reproduction. In the red blood cells, they develop into schizonts (feeding stage), which rupture the cells, releasing newly formed merozoites which then invade other red blood cells. Some of the merozoites in infected blood cells, leave a cycle of asexual replication. Instead of replicating, the merozoites in these cells develop into sexual forms of the parasite called male and female gametocytes. The cycle in mosquito starts when the mosquito bites an infected human and ingests gametocytes. The male and female gametes fuse to form diploid zygote, which develops into moving ookinete. The ookinete burrows in the midgut wall of mosquito, forming oocyst on the other side. Growth and division of each oocyst produce numerous active haploid forms called sporozoites. After 8 to 15 days (depending on the species), the oocyst bursts, thus releasing sporozoites into the body cavity of the mosquito, from where they travel to, and invade the mosquito salivary glands. The cycle of human infection re-starts when the mosquito taking a blood meal injects the sporozoites from its salivary glands into the human blood stream.

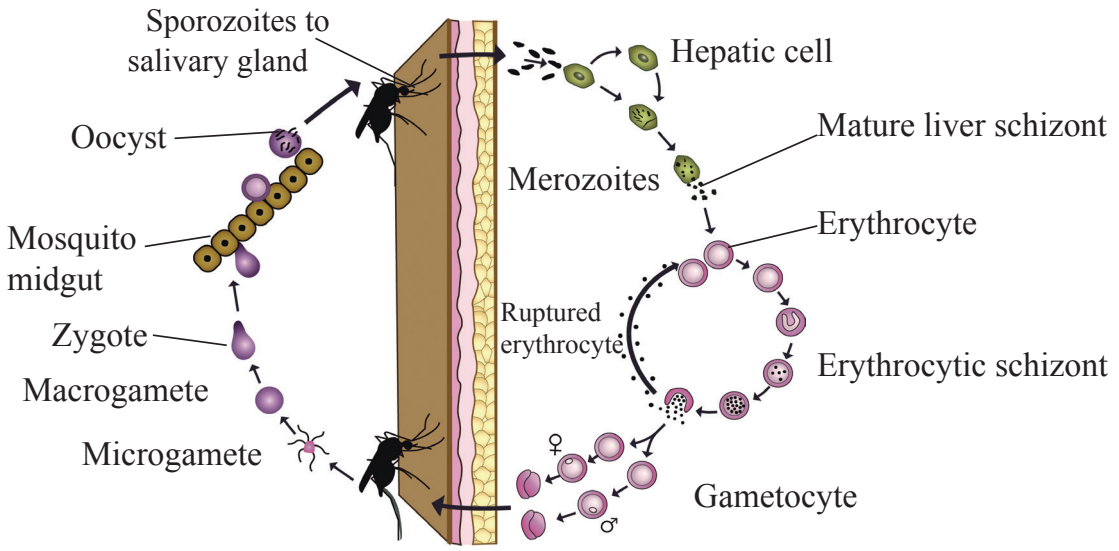


Figure 3.15 The life cycle of a *Plasmodium*

Adaptations of *Plasmodium* to its mode of life

Plasmodium, a parasite that causes malaria invades the human red blood cells as an essential step of its complex life cycle; it has the following adaptive features to its mode of life:

a) Presence of a well developed chemotactic responses which enable them find their way to the liver cells, then to the human red blood cells, gut epithelium, and eventually, to the salivary glands of mosquitoes.

b) They have enzymes which enable them to penetrate through the host cells such as liver and red blood cells of human as well as crop and salivary glands of mosquitoes.

c) *Plasmodium* has an extremely simple structure, which enhances its sheltered life within the bodies of the two hosts.

d) The ability to adjust their osmotic pressure in relation to the mammalian blood, mosquito's crop, haemocoel and salivary glands assures their existence in the mentioned parts.

e) They have gametocytes which can resist mosquito's digestive enzymes, and they have adapted to high reproductive rate by schizogony in liver cells, repeated schizogony in red blood cells, and sporogony in the mosquito salivary glands, to ensure their survival.

Exercise 3.5

1. Distinguish between Apicomplexa and other protoctists.
2. Describe the reproductive cycle of a *Plasmodium*.
3. *Plasmodium* is able to survive in its two different hosts. Justify.

Phylum Euglenophyta

This phylum comprises of unicellular aquatic algae, most of them live in freshwater; many possess flagella and are motile. The outer part of the cell consists of firm but flexible layer called a pellicle or periplast, which cannot properly be considered a cell wall. Some euglenoids contain chloroplasts that contain chlorophyll *'a'* and *'b';* the photosynthetic pigments, as in the phylum chlorophyta. Others are heterotrophic and can ingest or absorb their food. Food is stored as paramylon. Reproduction takes place by longitudinal cell division. The most common organism in this phylum is photosynthetic protozoan such as *Euglena*, usually found in water bodies like ponds.

General characteristics of phylum Euglenophyta

a) They have chloroplasts which contain chlorophyll for photosynthesis.

b) Most of them are found in fresh water; only few are marine dwellers.

c) They are protected by pellicle which surrounds the cytoplasm, since they lack cell wall. This enables the cells to change shape because they move around by euglenoid movement by the aid of myonemes.

d) They have two flagella. One of them is short, while the other is long; these arise from the bottom of a reservoir.

e) They have eye spot (photoreceptor) for detection of light intensity.

f) They have pyrenoids for storage of starch.

g) They sometimes feed heterotrophically by using the gullet.

Distinctive features of phylum Euglenophyta

Members of the phylum Euglenophyta are distinguished from other phyla by the following features:

a) They have pyrenoids for storage of starch.

b) They have eye spot (photoreceptor) for detection of light intensity.

c) They possess both plant and animal characteristics (Figure 3.16). Plant characteristics include; presence of chloroplasts containing chlorophyll, pyrenoids, and utilization of nitrites or ammonia as sources of nitrogen. Animal characteristics include; possession of myonemes (muscle- like strands), and flagella for locomotion (euglenoid movement), utilization of amino acids, peptones or polypeptide as a source of nitrogen, presence of gullet with sphincter and reservoir for ingestion of food.

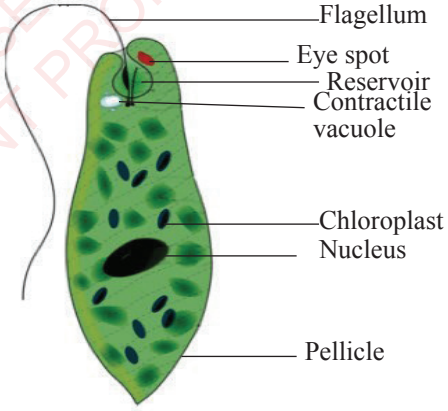


Figure 3.16 Structure of the *Euglena*

Adaptations of *Euglena*

Euglena is able to survive freely in its environment due to presence of the following adaptive features:

a) It has chloroplast which contains chlorophyll for photosynthesis.

b) It sometimes behaves as heterotroph due to possession of a gullet with sphincter and reservoir.

c) It can swim using flagella.

d) It has a flexible pellicle for maintenance of shape and aiding in euglenoid movement.

e) It possesses contractile vacuole for osmoregulation.

f) It has a high (rapid) rate of multiplication during favorable conditions and forms cysts under unfavorable conditions to ensure survival.

g) It has a photoreceptor for detection of light conditions.

Exercise 3.6

1. *Euglena* is believed to be the origin of both plants and animals. Explain.
2. Draw a well labelled diagram of *Euglena*.
3. Explain the adaptations of *Euglena* to its mode of life.

Phylum Oomycota

The phylum includes fungus-like organisms, which are also referred to as "water molds". Normally oomycetes may occur as saprotrophs; living on decayed matter or parasites living on higher plants and can be aquatic, terrestrial or amphibious. Oomycetes play an important role in the decomposition and recycling of decaying matter. Members of this phylum are fungi-like protoctists such as *Phytophthora, Puccinia* and *Pythium.*

General characteristics of phylum Oomycota

a) They are filamentous protoctists which must absorb their food from the surrounding water or soil, or may invade the body of another organism to feed.

b) They are mostly parasites of plants, example *Phytophthora infestans* which causes serious diseases such as potato blight disease.

c) They reproduce sexually by oogamy in which male and female gametes fuse to form an oospore.

d) The general body is organised into mycelia with aseptate or coenocytic hyphae.

e) They have cell walls made up of cellulose.

f) They have a tubular structure called a haustorium used for absorption of nutrients from the host (Figure 3.17).

Distinctive features of phylum Oomycota

Oomycota can be distinguished from other members of the group by the following features:

a) They have sporangia which produce zoospores.

b) Zoospore have two flagella attached to a ventral groove; the anterior flagellum

is a tinsel while the posterior one is a whiplash type.

Structure of *Phytophthora*

The vegetative body of *Phytophthora* consists of mycelium which is abundantly branched where septa may develop in the older parts and at the base of sex organs. The mycelium branches arise at right angles. The mycelium grows both intra- and intercellularly. During intercellular growth, it develops finger like haustoria inside the neighbouring host cells, which are normally the mesophyll cells of the plant leaves. The haustoria absorb nutrients from the leaf cells. The hyphae possess sporangium which produces spores (Figure 3.17).

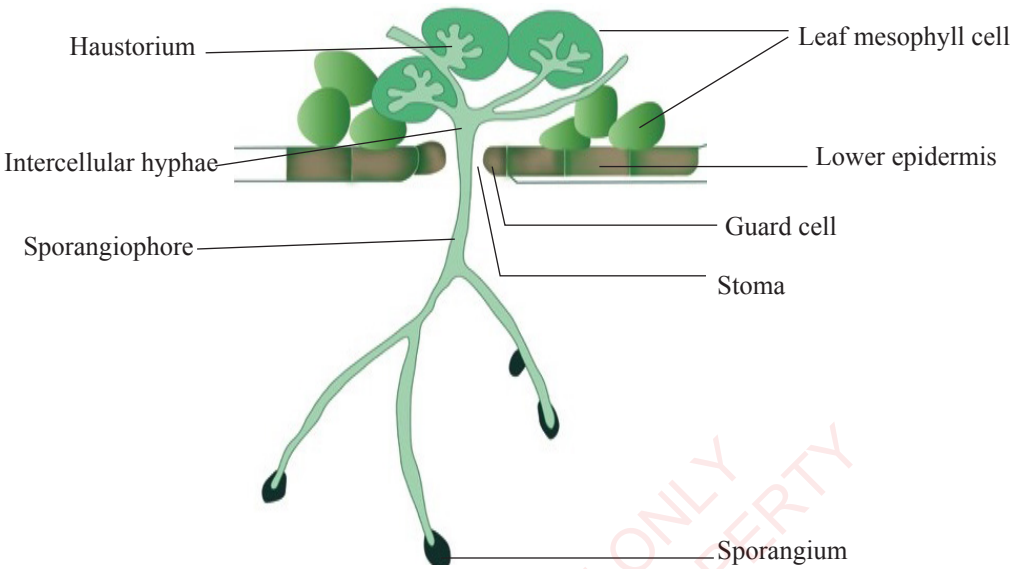


Figure 3.17 Structure of *Phytophthora infestans,* growing on an infected potato leaf

Adaptations of *Phytophthora* to its mode of life

The *Phytophthora* have the following adaptations to their mode of life:

a) Formation of cysts during unfavourable conditions ensures its survival.

b) Ability to reproduce both sexually and asexually, with a high reproductive output, increases its chances of survival.

c) It has haustoria with a large surface area for penetration into the plant cells and absorption of nutrients from them.

d) The haustoria secrete enzymes which help the parasite to penetrate its host cell.

e) It has spores which withstand the adverse conditions, such that, under favourable conditions, they germinate to *Phytophthora infestans*.

Exercise 3.7

1. Outline the general characteristics of *Phytophthora infestans*.
2. Why does *Phytophthora infestans* belong to kingdom Protoctista?
3. Explain the effects of *Phytophthora infestans* to plants and show how the spread of this parasite can be controlled.

Phylum Chlorophyta

Members of this phylum were formerly classified as plants. They include unicellular non motile alga (*Chlorella* and *Acetabularia*), a unicellular motile alga *(Chlamydomonas)*, filamentous alga (*Spirogyra)* and a thalloid marine alga, *(Ulva)*. In other classification, chlorophytes are placed under kingdom plantae, since they are more phylogenetically related to plants. They are regarded as ancestors of plants, because they have photosynthetic pigments such as chlorophyll '*a*', '*b*' and 'β' carotenoids as well as xanthophylls, which are characteristics of plants. Additionally, they possess photosynthetic apparatus called pyrenoid for condensation of glucose to starch, which is the same as photosynthetic product in plants. Under this phylum there are important species of high economic importance including sources of agar and phycocolloids, which are widely used in textile, pharmaceutical, and food industries. Chlorophytes are primarily aquatic, and are the primary source of energy and oxygen to marine heterotrophs. Few are found in special habitats in terrestrial environments.

Chlorophytes are heterogeneous in their pigmentation, shapes, and size. They range from microscopic, simple and unicellular such as *Chlorella* and *Chlamydomonas* to giant multicellular macroalgae. Although they resemble eukaryotic plants in many ways, they have no true roots, stem or leaves and do not produce seeds. The simplest structure is unicellular, but they may exist in colonies or in filaments of several distinct cells. Others may be multinucleated with interconnected cells that lack cross walls as in *Volvox* and *Oedogonium* respectively. This section will focus on the characteristics of chlorophytes, structure, and adaptations of *Spirogyra.*

General characteristics of phylum Chlorophyta

a) They are adapted to aquatic environments ranging from fresh to marine water, for example, their sexual reproduction relies on water as they produce motile sperms which have to move in water medium to fertilise the egg.

b) They are photoautotrophs and have chlorophyll '*a*' and '*b*' and other photosynthetic pigments such as carotenoids used in photosynthesis.

c) They have cell walls made up of cellulose.

d) They store carbohydrates in the form of starch.

e) They possess large vacuole for osmoregulation.

f) They occur in a great range of sizes and forms, including unicellular, filamentous, colonial and thalloid forms.

g) They reproduce both sexually and asexually; sexual reproduction involves specialised cells called sporocytes which undergo meiosis to produce haploid motile or flagellated cells called zoospores. These grow mitotically to form a gamete producing body called gametophyte, capable of producing either male or female reproductive cells (gametes). Female gametes can be either larger than male ones (anisogamous) or similar (isogamous) morphologically. Female and male gametes are flagellated, they can swim and unite to form a diploid zygote which settles and grows mitotically to form a multicellular body called sporophyte which can again produce sporocytes. The gametes, if not fertilised, lose their flagella and grow into a new gamete-producing body. Asexual reproduction occurs by vegetative fragmentation where individual cell or short chains of cells separated from the main body are capable of growing into a new body.

h) Life cycle of chlorophytes is diverse. For instance, *Ulva* shows an isomorphic alternation of generations in which sporocyte-producing body called sporophyte generation is morphologically identical to gamete-producing body called gametophyte generation. *Ulothrix* shows haplontic life cycle, in which sporophyte and gametophyte generation are morphologically different.

Distinctive features of phylum Chlorophyta

Chlorophytes are distinguished from other species of Protoctists by the following features

a) They have spiral chloroplasts with pyrenoids.

b) They have central suspended nucleus with cytoplasmic strands.

c) They show an isomorphic and haplontic alternation of generations.

Sturcture of *Spirogyra*

Spirogyra is a genus of filamentous green algae which have helical or spirally arranged chloroplast as a characteristic feature of this genus. They have thin strands of cytoplasm in which the prominent nucleus is suspended, and their spiral chloroplasts embedded in the cytoplasm bear the structure called pyrenoid for starch storage. The cell wall contains cellulose at the inner layer, and the outer layer contains pectin, which is responsible for the slippery surface of algae. Surrounding the cell wall, there is mucilage, which thickens the cell membrane, store water and food. Moreover, *Spirogyra* has long, unbranched filaments with cylindrical cells that are joined end to end. Each cell has a central vacuole. The cells are long and thin filaments, and sometimes these filaments develop root-like structures for attachment to the substrate (Figure 3.18).

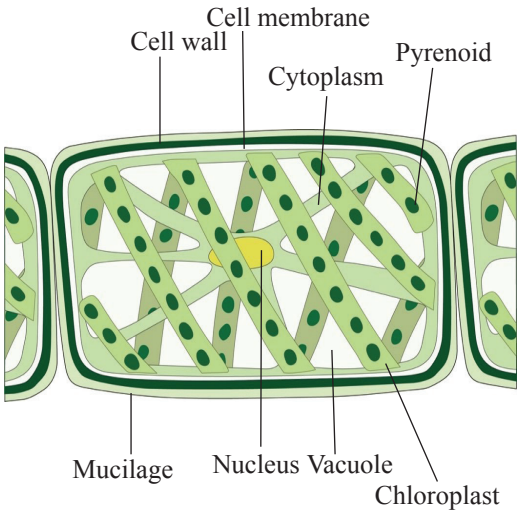


Figure 3.18 Structure of a *Spirogyra*

Adaptations of *Spirogyra* to its mode of life

Spirogyra is able to live and thrive in its environment due to the following adaptive features:

a) It has pyrenoids for storage of starch.

b) It has a large vacuole for osmo regulation.

c) It has chlorophyll *'a'* and *'b'* for photosynthesis, hence it is an autotroph.

d) It has mucilage layer to protect it from desiccation and infection.

e) It has a cellulose cell wall for strength and protection.

Activity 3.2 Observation of *Spirogyra* under a light microscope

Materials

Fresh *Spirogyra*, microscope, slides, slide cover, dropper, office pin, watch glass, and beaker containing water.

Procedure

a) Collect fresh *Spirogyra* from fresh water ponds or slow moving water streams, and put it into a watch glass.

b) Add a drop of water on a clean slide using a dropper, and using an office pin pick a few threads of *Spirogyra* and mount them on the slide.

c) Separate the strands using a pin to remain with a few threads. Cover your specimen with a coverslip.

d) Place the slide under a light microscope for observation.

e) Notice the wide variety of chloroplast types and the small, round, colorless pyrenoids on some or all the larger chloroplasts.

f) Based on your observation, draw and label the diagram of *Spirogyra* showing the pyrenoids, spiral chloroplast, mucilage, cytoplasm, and nucleus.

Exercise 3.8

1. Draw and describe the structure of *Spirogyra.*
2. Describe ways in which *Spirogyra* is adapted to its mode of life.
3. Explain the role of *Spirogyra* in oxygen balance in fresh water habitat.
4. With examples, explain why taxonomists sometimes regard *Spirogyra* as a plant.

Economic importance of kingdom Protoctista

Protoctista are mostly aquatic organisms found in sea, fresh water and moist soil. Many are also found in the form of plankton and some live in the bodies of animals as parasites. Some members of the kingdom Protoctista plays an essential role in the ecosystem that can benefit humans and other creatures. However, some members are important pathogens and can bring harm to living organisms. In some cases, Protoctista might be a source of pollution in lakes and coastal shores.

Advantages of kingdom Protoctista

Protoctists have the following economic importance:

a) Algae are edible and nutritious to humans and other animals. Some species are cultivated and harvested for consumption by human being. Red algae are rich in vitamins and minerals. Carrageenan, a polysaccharide extracted from red algae, is used as thick agent in ice cream and other foods.

b) Giant kelp forests (Large brown algae) are rich ecosystems, providing food and shelter for many organisms.

c) Trichonymphs are flagellates that live in the intestines of termites. These protozoans break down cellulose in wood into carbohydrates that termites can digest.

d) Algae and *Euglena* are primary producers in aquatic ecosystems. Most species are primary sources of food for aquatic organisms such as fishes and zooplanktons.

e) Some Protoctists are used as fish baits.

f) Algae species produces oxygen useful for aerobic respiration, particularly in the aquatic environment which is utilised by other aquatic organisms.

g) Some are used in agriculture as good sources or fertilizer. For example, liquid extracts from the brown algae supply potassium and trace elements such as zinc.

h) Some algae serve as a source of agar, used in the pharmaceutical industry in preparation of culture media for growing microbes, such as bacteria and fungi.

i) Some protoctists such as algae are milled or ground to obtain powder which is used as a thickener, binder, gelling or stabilising agents in the manufacture of various products such as cosmetics, paints, tooth paste, and ice cream.

j) Some protoctists such as *Entamoeba coli;* a non-pathogenic species of genus *Entamoeba*, can exist as a commensal parasite in the human gastrointestinal tract and feed on pathogenic bacteria.

Disadvantages of kingdom Protoctista

a) They cause pollution; the red algae cause water pollution called the algal bloom which may hinder boating and recreation.

b) They cause diseases to human beings; for instance, Amoebiasis is caused by *Entamoeba histolytica*, malaria is caused by *Plasmodium* species (like *Plasmodium malariae*, *Plasmodium vivax,* and *Plasmodium falciparum*).

c) Some members of the kingdom cause diseases to animals; for

example *Trypanosoma brucei* causes Trypanosomiasis (sleeping sickness) to humans, *Trypanosoma vivax* causes Nagana disease in cattle.

d) Some members cause diseases to plants. A good example is *Phytophthora infectans* which infect tomato and potato plants.

3. 5 Kingdom Fungi

Organisms belonging to this kingdom are those originally placed in kingdom Plantae under the two kingdom classification system. The early placement of fungi under kingdom Plantae was due to the morphological appearance of some fungi, particularly the mushrooms which resemble plants. The microscopic fungi were not yet known by then, since the microscopes were not yet invented. It was discovered later that fungi differ from plants in several ways, hence they were placed in their own kingdom, and most of them had economic importance. Through mycology (a study of fungi), over 100,000 species of Fungi have been described. It is estimated that there are over 1million species of Fungi waiting for identification.

Fungi are eukaryotic, unicellular or multicellular multinucleate organisms, made up of a mass of branching and delicate thread-like structures called hyphae, which collectively constitute fungal bodies called mycelium. Depending on the species, some hyphae may have cross walls called septa, dividing hyphae into many cells with one or more nuclei. In some species, the cytoplasm is continuous without cross walls. Fungi are thallophytes, lacking chlorophyll, hence nutrition in these organisms is either parasitic or saprophytic. Fungi produce extracellular enzymes which digest almost everything including protein and starch. The end products of digestion are absorbed by special structures called haustoria (*plural*) or haustorium (*singular*). Some fungi are parasites, as they obtain nutrients directly from other living organisms such as plants and animals. They have cell walls made up of chitin, unlike plant cell walls which are made up of cellulose. Organisms under this kingdom store carbohydrate in the form of glycogen like animals, but not starch, as in chlorophytes and plants.

They have a variety of shapes and sizes extending from microscopic to macroscopic. Sexual reproduction in fungi involves two haploid nuclei of compatible mating hyphae strains that unite to form a zygote which later grows into a new fungal body. Asexual reproduction is accomplished by production of asexual spore which, under favorable conditions, germinates and grows to form new haploid fungal hyphae. Examples of organisms in this kingdom include mushrooms, yeasts, *Penicillium*, bread mould, and toadstool.

Position of kingdom Fungi

As explained earlier, the position of fungi in classification was one of the controversial arguments. It was previously not clear whether fungi should be classified as an animal or as a plant, because they have some features in common for both plant and animal groups.

Similarities between fungi and animals

Similar to animals, fungi have the following features:

a) They have chitin as a structural carbohydrate in the cell wall. This is a feature typical of animals such as arthropods; example insects.
b) They store carbohydrates in the form of glycogen.
c) They are heterotrophs. Thus, they cannot manufacture their own food since they are either saprophytes or parasites. The parasitic fungi can be facultative or obligate.

Similarities between fungi and plants

Similar to plants, fungi have the following features:

a) Their cells have cell wall.
b) Some fungi have vegetative bodies that are superficially differentiated into shoot-like and root-like systems.
c) Most fungi's growth is restricted to apical cells.
d) They are non-motile.
e) They reproduce sexually by formation of spores such as ascospore in yeast and basidiospores in mushrooms. Some fungi reproduce asexually by producing spores such as sporangiospore.
f) They lack centrioles in their cells.

Fungi are heterogeneous kingdom consisting of several phyla. However, despite many ways in which fungal organisms are distinct, the major criterion used in grouping them into their respective groups is their reproductive structures. Within the kingdom Fungi there are three phyla, namely; Zygomycota, Ascomycota, and Basidiomycota.

Phylum Zygomycota

Fungi belonging to this phylum produce asexual resting spore called zygospore, which is produced when two opposite mating strains come close together and their haploid nuclei unite. The zygospores are resistant to breakage but they are light, hence they can be dispersed by wind and water. The structure of zygospore is capable of keeping the fungus over a long period of dormancy. Cells within the zygospore undergo meiosis to form haploid spores and when released in favorable conditions they germinate to form a new hyphae or mycelium. This phylum comprises of saprophytic fungi such as *Mucor* and *Rhizopus stolonifer*; a common bread mould. Zygomycetes can also reproduce asexually by spores born out of sporangia. Some zygomycetes are parasites in plants, insects, and animals.

General characteristics of phylum Zygomycota

a) They produce a characteristic sexual resting spore called zygospore.
b) They are eukaryotic organisms, with aseptate hyphae that have well developed branching mycelia. Aseptate means without septa or cross walls, and are sometimes called coenocytic.
c) They undergo both sexual and asexual reproduction. Sexual reproduction is by conjugation; this involves fusion of two haploid nuclei from the two mating hyphae or strains to produce zygospores. Asexual reproduction occurs via haploid spores released from sporangia.
d) They are saprophytes since they feed on dead decaying organic matter by

undergoing extracellular digestion. However, some zygomycetes are parasitic on plants, animals, and insects.

e) Their hyphae have three distinct parts, namely sporangiophore, stolon, and rhizoids.

Distinctive features of phylum Zygomycota

Members of the phylum Zygomycota have the following features that differentiate them from other phyla:

a) They have aseptate hyphae which lack cross walls between adjacent cells. They are therefore coenocytic in structure.

b) Their cytoplasm is continuous and multinucleate.

c) They undergo sexual reproduction involving two gametangia to produce a resting spore known as zygospore.

Structure of *Rhizopus*

The body of *Rhizopus* consists of branching mycelia composed of three types of hyphae; stolons, rhizoids, and normally branching sporangiophores (a stalk that arises from the vegetative hypha), and sporangia (asexual spore-forming structures) arise from stolons opposite to rhizoids (Figure 3.19). Stolons are the horizontal creeping hyphae that interconnect the upright growing hyphae. The sporangiospores are produced inside the spherical structure called sporangium which is supported by the columella.

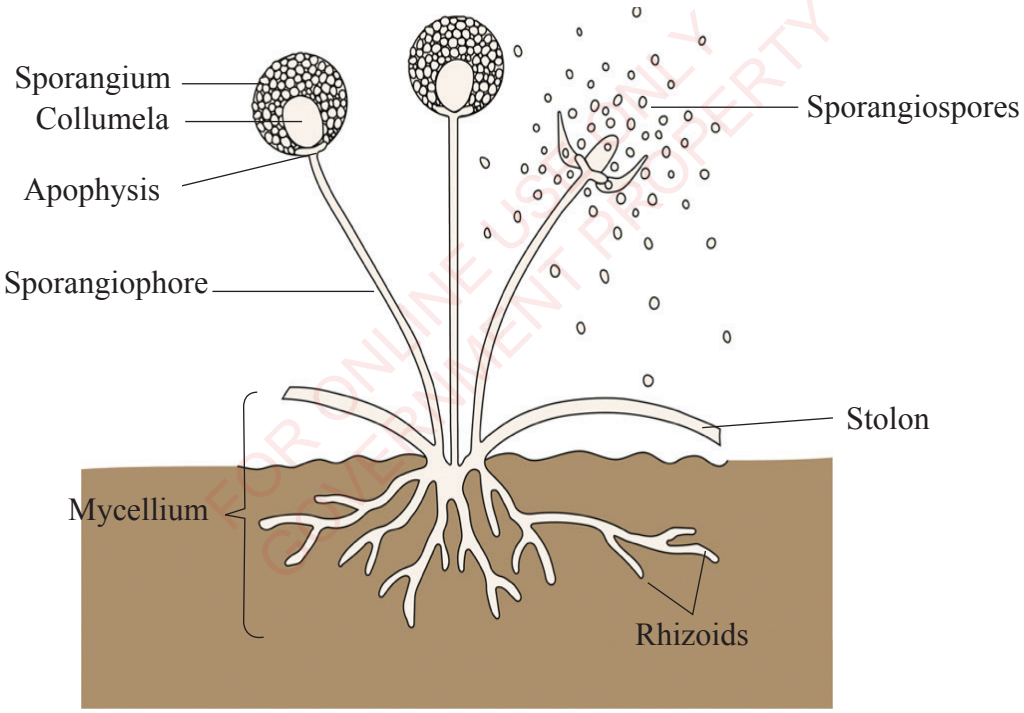


Figure 3.19 Structure of a *Rhizopus*

Adaptations of *Rhizopus* to their mode of life

Members of *Rhizopus* are saprophytic, and can grow and survive on various organic substrates including bread, mature fruits, and vegetables. They are able to acclimatize themselves to their environment due to the presence of the following adaptive features:

a) Pressure in columella makes the sporangium burst to release haploid spores. Each individual spore upon falling on conducive environment can germinate to a new hyphae body. These asexual spores are produced in large quantities; even in harsh conditions when the environment is dry, they ensure a quick spread of the species.

b) They have rhizoids for anchorage on the substrate and absorption of nutrients.

c) Their hyphae show chemotropism; in response to the digested food substances.

d) They produce thick-walled resistant, dormant zygospore. This enables the spores to withstand unfavourable and adverse conditions.

e) The wall of sporangium is so brittle that it easily breaks off to release the spores and ensure their multiplication.

f) Under asexual reproduction, they produce large number of spores to ensure survival of the species.

g) The spores are small and very light, and the sporangia are raised up to aid dispersal of spores by wind.

Activity 3.3 Observation of *Rhizopus*

Materials

Bread, petri or dissecting dishes, hand lens or light microscope, and slides.

Procedure

a) Take one slice of bread in a dish.

b) Leave it exposed on a bench for five to seven days, until black hairy-like structures appear on the slice.

c) Use a hand lens or a light microscope to observe the specimen on the slice. Carefully observe the upright hyphae with black spherical structures at their tips.

Questions

1. Draw a well labelled diagram of the observed specimen.
2. State the functions of each structure in the diagram you have drawn.
3. Identify the specimen by its common name.

Phylum Ascomycota

These are ascocarp forming fungi such as yeasts (*Saccharomyces)*, *Aspergillus*, and *Penicillium*. The ascocarp are cup-like structures containing small sacs which produce spores known as ascospores, resulting from sexual reproduction. Besides sexual spores, ascomycetes produce asexual spores called conidia, which develop at the tips of specialised hyphae called conidiophores. This is the most diverse group with about 30,000 described species.

Organisms in this phylum form many colourful cup shaped growths called morels on decaying logs of trees, fruits, crops, and foods. Most ascomycetes have highly branched hyphae. They are thus mycelia except yeasts, which are unicellular.

Yeast shows a number of differences in morphology, reproduction, and cell structure, when compared to other ascomycetes. Besides lacking hyphae, yeast does not have ascocarp, hence they are sometimes referred to as hemiascomycetes; meaning "half ascomycetes," to distinguish them from euascomycetes or true ascomycetes that have hyphae and ascocarp. They extracellularly secrete and produce enzymes such as protease (protein digesting enzymes) and cellulase (cellulose digesting enzyme). These kinds of enzymes make this group very destructive to animals, and plants. However, some ascomycetes such as yeast are widely used in brewing industries for production of alcohol through fermentation, while others are used in bakery and textile industries.

General characteristics of phylum Ascomycota

a) Their mycelium is made up of tightly woven septate hyphae except yeasts, which are unicellular.

b) They are heterotrophic saprophytes; in contrast to other members are parasites. For example, *Candida albicans* are infectious ascomycetes which cause mouth thrush. In plants, they are responsible for powdery mildew which infects cereal grains.

c) They have a fruiting body containing several sac-like structures called asci (singular ascus) which produce haploid spores called ascospores. These spores can germinate to form new haploid hyphae.

d) They possess conidia which are found at the apex of hyphae called conidiophores which produce millions of resistant spores used in asexual reproduction.

e) Sexual reproduction is accomplished by mating of compatible hyphae forming a dikaryotic hyphae; that is hyphae with two nuclei in their cell. The nuclei will fuse only after the formation of ascus. The diploid nucleus will later undergo meiotic and mitotic divisions to form ascospores.

f) Some ascomycetes such as yeasts are unicellular and reproduce asexually by budding (new cells form on the surface of the old ones).

Distinctive features of phylum Ascomycota

The following are the distinctive features of the phylum Ascomycota:

a) They have specialised spore producing structures called ascocarps.

b) They reproduce asexually using conidia formed on the tips of conidiophores; in some members asexual reproduction is through budding.

c) Some are unicellular heterotrophs, and lack typical hyphae, for example *Saccharomyces.*

Structure of *Saccharomyces*

Saccharomyces are flat, smooth, and moist. They are unicellular, and they lack hypha. They have eukaryotic organelles such as mitochondria, ribosomes, Golgi apparatus, vacuoles and ribosomes which are found within the cytoplasm (Figure 3.20). The cell walls of *Saccharomyces* are elastic, determine the shape of the cell, and provide osmotic and physical protection.

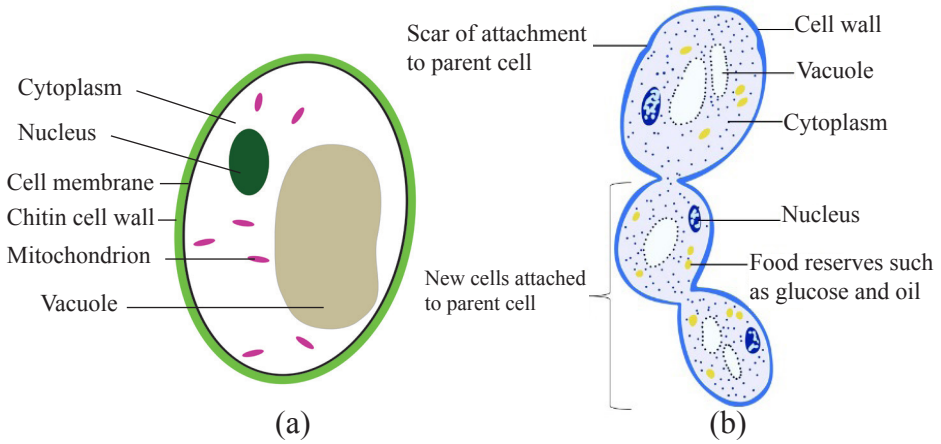


Figure 3.20 Structure of *Saccharomyces* (a) a single cell (b) a budding cell

Adaptations of *Saccharomyces* to its mode of life

Saccharomyces species have the following adaptive features that enable them suit to their mode of life:

a) They store carbohydrates in the form of glycogen for use during shortage of food supply.

b) They have permeable cell walls to allow entry of nutrients that are obtained from external digestion. Thus, they can absorb simple monosaccharides and vitamins directly from their environment.

c) They secrete extracellular enzymes such as sucrase and cellulase for digestion of carbohydrate, and protease for digestion of protein.

d) They have high reproductive rate through budding, to produce new cells hence increase in number.

e) Spores' ability to remain dormant in unfavourable conditions ensures their existence.

f) Some *Saccharomyces* are facultative anaerobes. They have an ability to respire anaerobically or aerobically, which ensures survival in both aerobic and anaerobic conditions.

Activity 3.4 Observation of yeast cells under light microscope

Materials

Yeast cells, water, beaker, stirring rod, dropper, slides, and microscope.

Procedure

a) Put some yeast in a beaker containing small amount of water, then stir to get a suspension.

b) Add a drop of suspension using a dropper, put it on a clean slide.

c) Observe the specimen under a light microscope.

Questions

1. Draw and label a diagram of the specimen under observation.
2. Classify yeast to phylum level.

Exercise 3.9

1. In which ways are Ascomycetes similar to and yet different from Zygomycetes?
2. With examples, explain why yeast *(Saccharomyces cerevisiae)* is not a good representative of phylum Ascomyota, but it is still classified under the same phylum.
3. Describe the adaptations of yeast to its mode of life.
4. In which ways are Ascomycetes economically important in our daily life?

Phylum Basidiomycota

This phylum consists of basidiomycetes which contains about 25,000 species. It is the most common and widely known phylum of kingdom fungi. Organisms in this kingdom include mushrooms, bracket fungi, puffballs, smuts, rust and toadstools. Some basidiomycetes are parasites, while others are saprophytes. Bracket fungi cause damage to plants. For example *Puccinia graminis* causes wheat rust; smuts infest cereals, among other plant species. Saprophytic basidiomycetes include the edible mushroom *Agaricus campestris* while others like *Amanita virosa* are poisonous. In addition, symbiotic association called mycorrhizae are common between basidiomycetes and roots of higher plants.

This phylum got its name due to the presence of a characteristic club shaped structure known as a basidium (*plural* basidia) from which basidiospores are produced. Basidiospores are characteristic sexual reproductive structures of basidiomycetes. Individual basidia are fused to form basidiocarp, which is the most spectacular and familiar stage of most basidiomycetes such as mushrooms. Species in this phylum have septate hyphae with distinct small pores. Haploid hyphae of basidiomycetes like mushrooms fuse to form a dikaryotic mycelium called stipe, growing upright and culminate into an umbrella-like cap called basidiocarp in which the hyphae are tightly packed. The hyphae tips are swollen forming a characteristic club-like structure (basidia) in which the dikaryotic nuclei fuse and later meiotically divide to form four haploid basidiospores. These are ejected out of the basidia through four fingerlike projections at the tip of each basidium. Each spore can germinate to form new haploid hyphae. Evolutionarily, basidiomycetes are more closely related to ascomycetes than to the other phyla. The basidia function in a similar way as ascus.

General characteristics of phylum Basidiomycota

a) They have a characteristic cap-like structure called basidiocarp, which

contains numerous club-like structures known as basidia from which haploid, sexually reproduced spores (basidiospores) are produced.

b) Sexual reproduction in most basidiomycetes results into the formation of dikaryotic hyphae

c) They have septate hyphae.

d) Some basidiomycetes are saprophytes while others are parasites.

Distinctive features of phylum Basidiomycota

Members of phylum Basidiomycota possess some features which differentiate them from the other phyla. These features include:

a) Basidium formed at the tips of hyphae is a characteristic sexual spore producing structure in which union of dikaryotic nuclei occurs, followed by meiosis to produce haploid basidiospores.

b) Hyphae have septa with distinctive pores.

Structure of *Agaricus*

Members of *Agaricus* consist of a stalked fruiting body with pileus on its top (a fleshy cap), which in turn bears numerous radially arranged gills on its basement. The vegetative mushroom body is also called mycelium. The underground hyphae have minute threads called rhizoids, as a group are also known as mycelium threads. They are located underneath the fruiting body, and they store and supply the nutrients to the mushroom. These structures anchor the mushroom to the substrate, while the stipe (stem) make it stand upright (Figure 3.21). Cup (volva) is found below the stem while the ring (annulus) surrounds the stem.

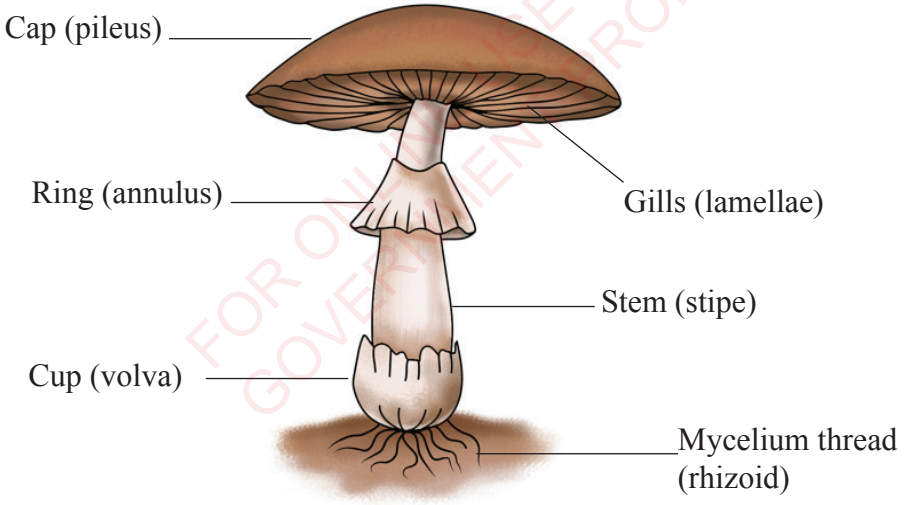


Figure 3.21 Structure of an *Agaricus*

Adaptations of *Agaricus* to its saprophytic mode of life

Members of the genus *Agaricus* are adapted to saprophytic mode of life. The adaptations of *Agaricus* to its mode of life are as follows:

a) They have ability to secrete a variety of hydrolytic enzymes for extracellular digestion of various organic matters.
b) They possess rhizomorphs which are responsible for absorption of nutrients from the substratum.
c) They have stipe for upward transport of nutrients to reach cap cells.
d) They store carbohydrates in the form of glycogen for use during shortage of food supply.
e) They are able to grow and survive on different substrata to increase chances of survival.
f) They produce large numbers of very tiny and resistant basidiospores which are easily dispersed and resistant to harsh conditions.
g) They have pileus or cap made up of closely packed hyphae to confer protection to the gills.

Activity 3.5 Observation of a mushroom

Materials

Fresh or preserved mushroom, hand lens or light microscope, petri dish, and a pair of gloves.

Procedure

a) Wear a pair of gloves on your hands and collect a fresh or preserved specimen of mushroom and put it in a petri dish.
b) Observe the specimen using a hand lens or under a low power of the light microscope.
c) Take note of the gills radiating out from the stalk (stipe) like the spokes of the wheel.
d) Examine part of the gill under high power and note the presence of tiny club-shaped basidia lining one side of the gill. Sometimes, small finger-like projections at the tips of basidia are visible in which black spots 'basidiospores' are found.

Questions

1. Draw and label the structure under observation.
2. Outline the adaptive features of the specimen to its mode of life.

Safety precaution

Some mushroom species are poisonous when consumed, so be careful when dealing with mushrooms.

Economic importance of Fungi

Although some fungal species are pathogenic that may cause disease in plants and animals. Most fungi are saprophytic and not pathogenic to plants and animals are important to human life at many levels. Fungi play an important role in medical industry, agriculture, research and in the ecosystem.

Advantages of kingdom Fungi

a) Some members of the kingdom Fungi such as *Agaricus* species are source of food to human being. For example *Agaricus bisporus* are the most important edible mushroom commercially cultivated world-wide. They are rich source of nutrients such as proteins, carbohydrates, lipids, minerals, fibres, and vitamins. They can be used as nutritional supplements to humans. They can also be used for medical therapy: as antimicrobial, anticancer, and antioxidant roles. Other animals such as ants and millipedes feed on fungi.

b) Yeasts are used in fermentation to produce alcohol in brewing industries.

c) Fungi are important in production of organic acids and organic solvents such as acetic acid, lactic acid, amyl, isoamyl alcohol, and glycerol.

d) Saprophytic fungal communities are important in the soil as they decompose dead organic matter and recycle nutrients locked in dead plants and animals thereby improving soil fertility.

e) Some members of the kingdom Fungi are used in producing medicine (antibiotics) such as penicillin from *Penicillium* sp., and ephedrine extracted from yeast.

f) They are sources of important hormones such as gibberellins obtained from *Gibberella fujikuroi*. This hormone regulates vegetative and fruit growth in plants.

g) They are important in cheese industry and in production of some enzymes such as amylase.

h) They are used in research such as biochemical genetics; a good example is *Neurospora crassa* (ascomycetes) which is used in many aspects of cell biology and biochemistry to elucidate various molecular events involved in epigenesis, cell fusion and development.

i) Fungi, particularly the genetically engineered ones, can be used in bioremediation to degrade some pollutants in the environment. They are useful in detoxification of poisonous substances such as cyanide which is removed from cassava by moulds, such as *Rhizopus*.

j) Saprophytic fungi are used as scavengers in sewage treatment to clean the environment. Some fungi with the ability to digest cellulose are used in waste papers' disposal.

k) Some fungi are grown for commercial production in order to extract pigments which are used in the preparation of various dye materials.

l) Some fungi can be used in biological control as they obtain their food by destroying other organisms like amoeba, rotifers, and nematodes. In addition, entomogenous fungi are parasitic on insects and other small anthropods such as mites and spiders.

m) They are involved in symbiotic mycorrhizal association with roots of vascular plants in which they increase the plant roots' surface area for absorption of nutrients of nutrients, while, in turn, the fungi get some of the photosynthesized food from plants.

n) They are used in biological studies as specimens, for instance *Rhizopus, Saccharamyces,* and *Agaricus*.

Disadvantages of kingdom Fungi

a) Some fungi produce toxins that can affect plants and animals, for example

some fungi are so poisonous that when consumed by mammals they can cause death. An example of poisonous mushrooms is *Amanita.*

b) Some fungi cause diseases, for example, ringworms (dermatophytosis or tinea) are fungal skin infection in animals and smuts in plants.

c) Foods such as grains, tubers, and fruits can be destroyed by saprophytic fungi such as *Mucor* and *Rhizopus* if not well stored.

d) Saprophytic fungi deteriorate organic materials such as leather, natural fabrics, and damp timber, example mold leather, mildew and wet rot fungi.

e) When accidentally consumed in food, some fungal species affect the nervous system and may cause hallucinations, example an invasive fungus called *Cryptococcus* may cause a serious inflamation of brain and spinal cord, the condition known as cryptococcal meningitis.

f) Some fungi such as the *Penicillium,* which are used in pharmaceutical and cheese industries, cause various types of allergic conditions to some people.

Exercise 3.10

1. With examples, explain how mycology and its application can be an important step towards industrial revolution in Tanzania.
2. Give reasons to justify the position of fungi in their kingdom.
3. What is the single important factor considered in classifying fungi into different phyla? Give an example for each phylum.
4. Explain why the placement of fungi under the kingdoms Plantae and Animalia was confusing early taxonomists.
5. Briefly explain why ascomycetes and basidiomycetes are evolutionarily related.

3.6 Kingdom Plantae

Plants can be broadly defined as multicellular eukaryotic photoautotrophs. They contain chloroplasts which have chlorophylls '*a*' and '*b*'. Some plants contain photosynthetic pigment called carotenoid which is used for photosynthesis. Their cells have cell walls made up of cellulose and have large permanent vacuoles. Plants store carbohydrates in the form of starch. They reproduce sexually by production of spores and vary from primitive to advanced plants. The most primitive plants such as Bryophytes produce spores which are of the same kind and size (homospores) and the plants are termed homosporous. On the other hand the advanced plants, including a few species of ferns and all seed producing plants are heterosporous, as they produce two types of spores: micro and macro spores. Plants exhibit alternation of generations in which a haploid gamete producing phase called gametophyte generation alternate with the diploid spore producing phase called sporophyte generation. Plants are sessile, meaning that they have limited locomotion but show curvature movements. Their vegetative body is divided into root and shoot systems.

Plants are believed to have evolved from an aquatic ancestor which was probably *Ulotricales* algae stocks. Life on land started about 0.5 billion years ago when the earliest plants started to establish their life on land. The earliest plants were very tiny and were not well differentiated in roots, stem, and leaves. In addition, they had no vascular tissues. Water was absorbed to their bodies by simple diffusion. They produced motile sperms which restricted their habitats to wet areas or seasonally wet areas.

Early plants slowly adapted to terrestrial habitat by developing features such as cuticle to protect them from desiccation, development of roots and vascular system for water uptake and movement, and translocation of food. Furthermore, in sexual reproduction, fertilisation was taking place inside the female reproductive structure called archegonia, within which zygote development occurs. This was important to protect the delicate zygote from desiccation. The most advanced plants overcome dependence on water in reproduction by producing special tubes called pollen tube to carry sperms to the female reproductive organs for fertilisation. Plants can reproduce asexually in various ways, including through the use of gemmae as in bryophytes, and using various other types of vegetative reproduction such as fragmentation and cuttings.

Members of the kingdom Plantae are heterogeneous in many features. Among key aspects used in the classification of plants is alternation of generation. The features characterising each phase of generation are: types of spores, spore producing features, vascular tissue, ability to produce seeds, and flower formation. Among others, these features have led to the classification of plants into four divisions, namely Bryophyta, Filicinophyta (or Pteridophyta), Coniferophyta (or Pinophyta) and Angiospermophyta.

3.6.1 Division Bryophyta

Bryophytes are the most primitive terrestrial plants. They resemble the most advanced algae species in certain ways especially their dependence on water in sexual reproduction and lack of conducting tissues. Unlike algae, they form a zygote which is protected in the female reproductive structure called archegonium that safeguards the zygote against physical damage and desiccation. Most bryophytes have poor vegetative differentiation because they are thallose (or thalloid). The lack of conducting tissues (xylem and phloem) in bryophytes, unlike in other divisions of plants, is a challenge in terrestrial environments where water is limited.

However, water can simply be absorbed over their surface as they have various structural features to ensure the absorption of water falling on their surface. For instance, their leaf-like structures are overlapping, and have small warts on them to delay escaping water. In addition, they do not grow tall, hence, water can rise by capillarity, and they also have rhizoids for anchorage and easy absorption of water and mineral salts from the soil surface. Bryophytes include mosses, hornworts, and liverworts.

Traditionally, bryophytes were classified into two classes, namely Musci and Hepaticae. Members of class Musci include moss plants (*Funaria* sp.), while members

of class Hepaticae include liverworts (*Pellia* sp). A recent classification splits bryophytes into three classes, namely Hepaticopsida (Liverworts), Bryopsida (Mosses), and Anthoceropsida (Hornworts).

General characteristics of division Bryophyta

a) They show alternation of generations in which the haploid gametophyte generation is dominant over the diploid sporophyte generation.

b) The sporophyte is attached on the gametophyte generation, and it depends upon it for support and nutrition.

c) The gametophyte generation is anchored by filamentous rhizoids which provide support and used for absorption of water and mineral salts.

d) They lack vascular tissue, meaning that they have no xylem and phloem.

e) They have a thallus body which shows low level of differentiation; hence, they lack true leaves, stems, and roots.

f) They have a sporophyte generation, which produces homospores. Upon landing on a conducive environment, the spores can germinate to form the gametophyte generation on which male and female reproductive structures develop. They undergo sexual reproduction which involves multicellular sex organs called antheridia (male sex organs) and archegonia (female sex organs).

g) They are found mainly in damp and shady environment because their sexual reproduction depends on water, which facilitates mobility of their sperms.

h) Asexual reproduction is by fragmentation in which a small part can detach from the mother plant to form green multicellular reproductive bodies of different shapes called gemmae. Gemmae is formed in gemma cups on the leaf surfaces, stem apex or inside the cells. Each gemmae can germinate to form a new gametophyte upon falling on a suitable substrate.

i) They contain photosynthetic pigments (chlorophyll) as that of higher plants.

Distinctive features of division Bryophyta

Bryophytes possess the following features which differentiate them from members of other divisions:

a) They lack conducting tissue such as xylem and phloem.

b) They do not possess true stem, leaves, and roots. They have rhizoids instead of roots and they also lack cuticle; therefore, absorption of water and mineral salts in species such as liverworts takes place over the whole surface of the plant by diffusion.

c) They have a dominant gametophyte generation, on which sporophyte generation is attached and depends on gametophyte for food and support.

d) They are homosporous and their haploid spores germinate into a characteristic structure called protonema, which are filament of cells that later grow to form gametophytes.

Structure of *Funaria* sp.

A mature *Funaria* plant is structurally erect, measuring only a few centimetres above the ground. It is clearly differentiated into stem-like and root-like systems. The stem-like structure bears leaf-like structures that are arranged spirally along it. At the base of the "stem" are tuft of adventitious rhizoids that are used for anchorage and absorption of water and mineral salts. The greenish part of the plant (that is the stem-like structure and leaf-like structure), and the rhizoids constitute a gametophyte body (Figure 3.22). The sporophyte has a capsule which encloses the spores and their sex organs (antheridia and archegonia) which are borne at the tips of stem-like structures. *Funaria hygrometrica* is the most common moss species.

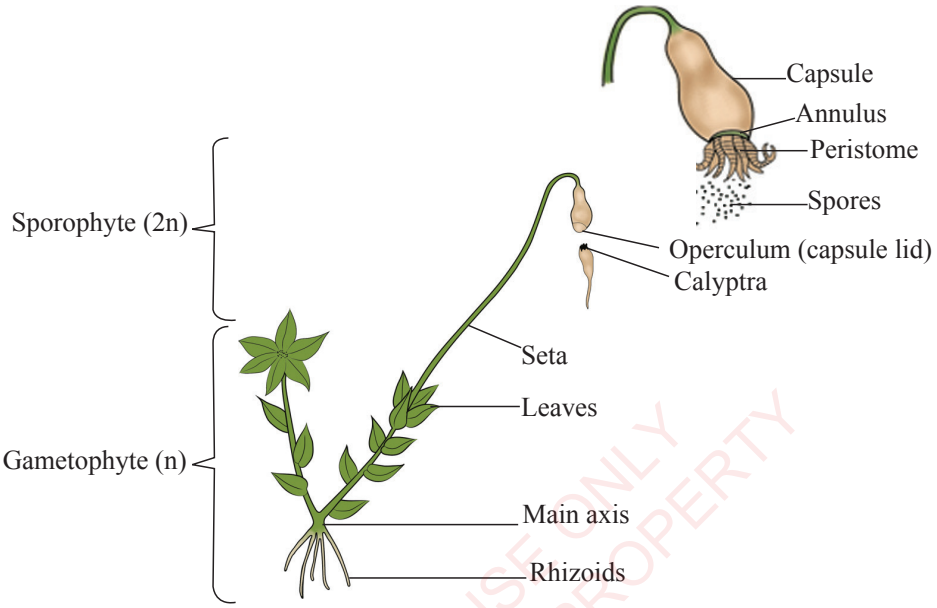


Figure 3.22 Structure of a *Funaria*

Reproduction of *Funaria*

A mature gametophyte of genus *Funaria* consists of short stem-like structure in which antheridia and archegonia are borne at the tips of the male and female stems respectively. Sexual reproduction requires water which is an essential medium for sperm swimming from the male gametangium (antheridium) to female gametangium (archegonium). Normally, when it rains, these small stem-like structures become flooded, saturated, swollen, and they burst to release sperms on the surface. The sperms produced have two flagella (bi-flagellate spermatozoids); hence, they can swim towards the egg (oogonium) located in the archegonium. Fertilisation takes place inside the archegonium to form a diploid zygote. It keeps growing while still inside the archegonium to form a stalk-like structure called seta which is a young sporophyte. This structure later matures and produces capsule on its tip. This means the entire sporophyte (seta and capsule) grows on the gametophyte, where it is supported and

supplied with food. The capsule produces spores which, once released, can germinate to form another gametophyte. The cycle repeats over again (Figure 3.23).

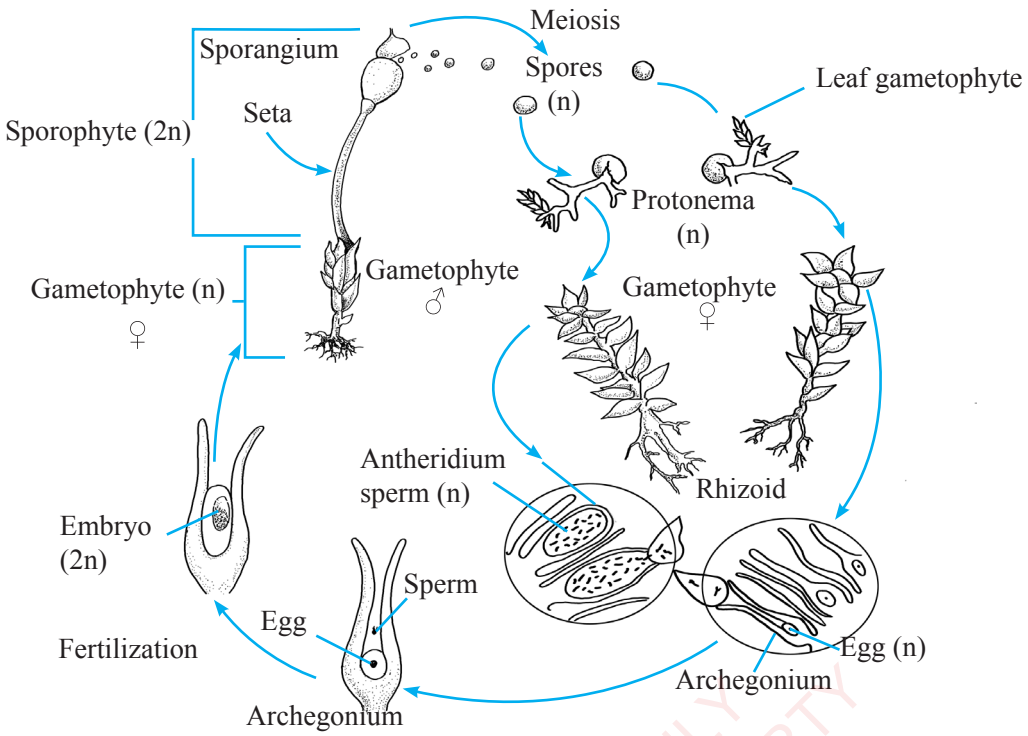


Figure 3.23 The life cycle of a *Funaria*

Activity 3.6 Observation of moss plant

Materials

Moss plant, hand lens or light microscope, and petri dish.

Procedure

a) Collect fresh moss plants from damp areas, wet walls, or tree barks.

b) Take a single moss plant and put it on a petri dish.

c) Observe the specimen using hand lens or light microscope. Note the greenish part and a small stalk growing on it; bearing a small club-like structure at the top.

Questions

1. Draw a well labelled diagram of what you have observed.
2. Compare your diagram with that of Figure 3.22.

Adaptations of *Funaria* to its mode of life

Members of *Funaria* have the following adaptive features:

a) They have chlorophyllous "leaf-like structures" for photosynthesis.

b) They have limited heights to overcome problems associated with lack of vascular tissues. Water and mineral salts can move up by capillarity in their short stems.

c) They possess rhizoids for anchorage on soil as well as absorption of water and mineral salts.

d) Male gametes, antherozoids, are biflagellate for swimming into archegonia.

e) They produce small and light spores that are easily dispersed to allow colonization of new areas.

f) The spores are tolerant to long periods of unfavorable conditions due to the presence of a thick wall with sporopollen in one of the major chemical component (polymers) on the outer wall of the spores.

g) They have elongated seta to expose the capsule to air for easy dispersal of spores.

h) Archegonia secrete chemical attractants which attract antherozoids to swim towards the egg during fertilisation.

Exercise 3.11

1. Briefly explain how bryophytes have managed to overcome various challenges in terrestrial habitats.
2. Explain why bryophytes are regarded as amphibious plants.
3. Outline the distinctive features of division Bryophyta.

3.6.2 Division Filicinophyta (Pteridophyta)

Members of division Filicinophyta are called pteridophytes. Examples of pteridophytes include ferns. Pteridophytes inhabit damp shady environments, such as on the floor of moist forests and river banks. About 1100 species of ferns are currently identified. Ferns are related to bryophytes in several ways, indicating that they might have probably descended from bryophytes. For example sexual reproduction in pteridophytes depends on water like in bryophytes. Moreover, like bryophytes, the pteridophytes' zygotes are retained and develop inside the multicellular archegonium. However, unlike bryophytes, pteridophytes exhibit alternation of generation in which the sporophyte generation is dominant over gametophyte generation which is relatively reduced and dependent on sporophyte. Ferns are also heterogenous in size and shape, ranging from filiform ferns to tree like ferns which can grow to approximately 20 metres tall and with broad leaves known as fronds. A fern tree called *Cyathea manniana* is very common in most parts of the eastern arch

mountain forests of Tanzania such as the Udzungwa scarp forest reserve. This fern can grow to a height of about 5 metres. Ferns have conducting tissues (xylem and phloem) which are not well developed and are sometimes termed as tracheophytes. While most pteridophytes are homosporous, some of the fern species produce two types of spores (heterosporous). Besides the pteridophytes, which are regarded as true ferns, other plant species called fern allies are not true ferns, though they relatively resemble pteridophytes in various ways. For example they disperse by shedding spores to initiate an alternation of generation. An example of a common fern is *Dryopteris filix-mas,* found in damp woods and other shady places.

Structure of *Dryopteris* sp.

A mature fern plant has an underground creeping stem called rhizome. This bears adventitious true roots for anchorage and absorption of water and mineral salts from the soil. It has broad leaves called fronds attached to the rhizome by a long stalk or petiole. Characteristically, the young leaves show a tightly rolled structure called circinate leaves or croziers which later unroll to reveal fronds with a stalk or petiole at the base. The bases of the fronds are covered with dry brown scales called ramenta for protection of young leaves against drought. The frond has a midrib called rachis, which bear leaflets called pinnae on both sides and small rounded sub-divisions of pinnae called pinnules (Figure 3.24).

The mature frond bears specialised reproductive structures called sori (clusters of sporangia) on the lower surface of the frond. The sporangia contain spores; therefore, sporangia bearing leaves are called sporophyll (*sporo* meaning spore and *phyll* meaning leaves). The *Dryopteris* species have poorly developed vascular tissues with simple xylem elements for the mechanical support and transport of water and mineral salts, while phloem elements are mainly for the translocation of synthesized food.

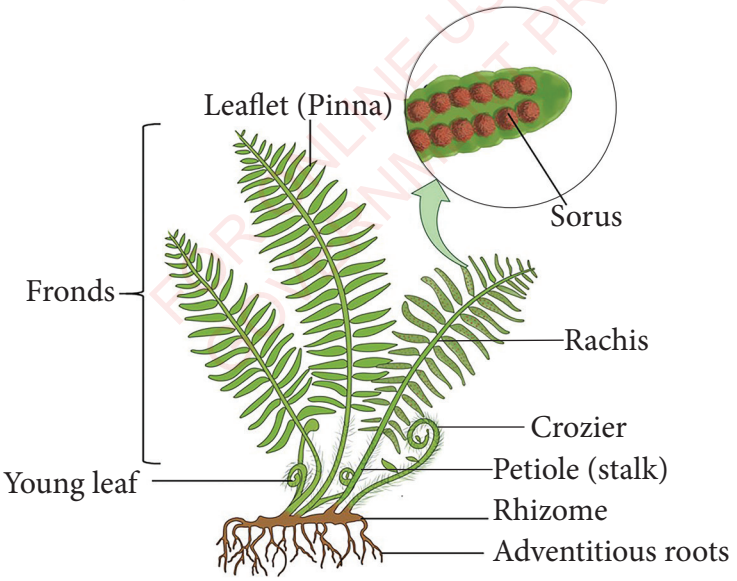


Figure 3.24 Structure of *Dryopteris* sp. showing sori at the lower side of the frond

Reproduction in *Dryopteris*

The diploid sporophyte generation have a cluster of sporangia (sori) in which the spore mother cell undergoes meiotic division to produce haploid spores. When the sporangia mature they break and release the spores. In favorable conditions, the spores germinate into a small green heart-shaped structure called prothallus forming a haploid gametophyte generation, bearing male and female reproductive structures (antheridia and archegonia), and rhizoids. The archegonia produce female gametes while the antheridia produce flagellated male gametes which swim to the archegonia in the presence of water to fertilise the egg, forming a zygote. The zygote develops to form a sporophyte generation with a horizontal stem (rhizome) and leaves. The gametophytes shrink and degenerate (Figure 3.25).

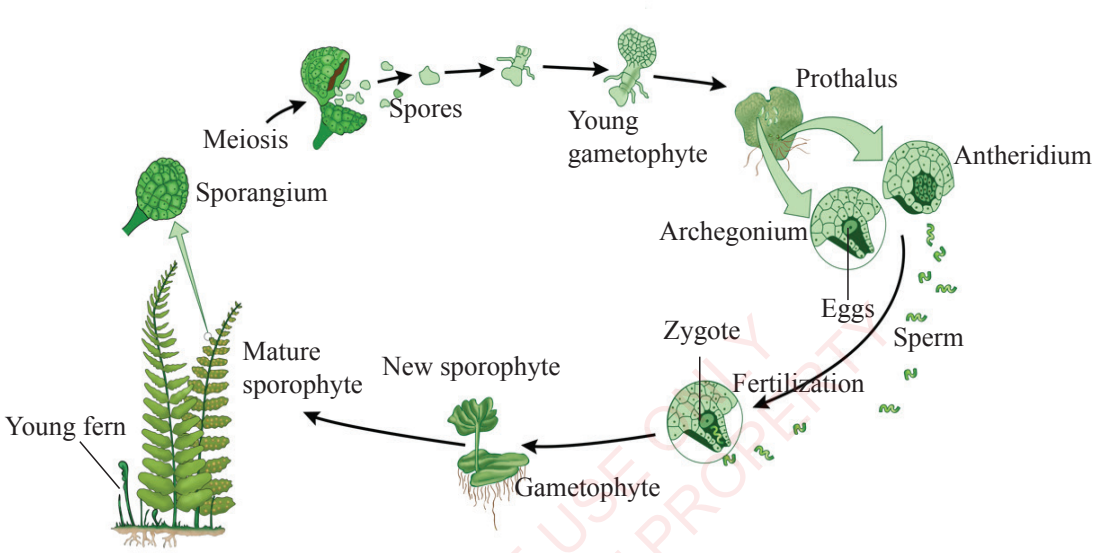


Figure 3.25 The life cycle of a fern plant *(Dryopteris)*

Adaptations of *Dryopteris* **to its mode of life**

Dryopteris possess the following features which enable them to adapt to their environment:

a) They have chloroplasts containing chlorophyll for capturing light energy needed for photosynthesis.

b) They have roots for anchorage and absorption of water and mineral salts.

c) They have stomata which facilitate gaseous exchange.

d) They have xylem responsible for transportation of water and dissolved minerals and also they have phloem for translocation of manufactured food.

e) Rhizomes play part in storing food and propagating new plants, and can remain viable in the soil for a long time to ensure survival.

f) They have a well-developed and independent sporophyte generation, since the gametophyte withers and dies as the young leaves of sporophyte grow.

g) They have cuticle in their leaves to prevent excessive water loss.

h) Archegonia secrete chemical which attracts antherozoids to swim towards the egg during fertilization.

Activity 3.7 Observation of fern plants

Materials

Mature fern plant (*Dryopteris* sp.) and hand lens or light microscope.

Procedure

a) Collect a mature fern plant (*Dryopteris* sp.) from a damp shaded area such as in the forest, floor or water canal or river bank.

b) Uproot the plant with a small part of the rhizome and roots.

c) Carefully examine the collected fern plant. Take note of the fronds (leaves) arising from the horizontal stem (rhizome).

d) Turn the frond and observe its lower side with the aid of a hand lens or a light microscope. Note small dark or brown patches on the lower side of mature fronds. Each discrete patch is called sorus.

Question

Draw a diagram to show the morphology of the specimens provided and indicate the sporophyte, frond, sorus, rhizome, and rhizoids.

Exercise 3.12

1. You are consulted by a friend who is raising ferns in his garden for the first time. He needs your advice on what appropriate measures he should take to rescue his fern plants, that appear to have a lot of dust brown spots on the lower side of the leaves, which were not there when they were young. Based on your knowledge of ferns, advice him accordingly.
2. Give reasons as to why ferns are considered to have evolved from bryophytes.
3. In which ways are ferns more adapted to terrestrial environment than bryophytes?

3.6.3 Division Coniferophyta

Coniferophyta is a division of kingdom Plantae which belongs to a broad group of non-flowering seed bearing plants, referred to as gymnosperms. The word *gymnosperms* originated from a combination of two Greek words *Gymno* meaning 'naked' and *sperma* meaning 'seed.' Theophrastus was the first person to use this term in his book "Enquiry into plants" referring to plants producing naked seeds. Under gymnosperms, there are four groups namely:

a) Conifers; the cone bearing plants such as cypresses; example: *Cupressus* species (Figure 3.26), pines; example: *Pinus sylvestris*, and Spruce; *Picea* species, which are the most abundant Gymnospermous species.

b) Cycads, the palm like plants.

c) Gingkos, examplified by only one extant species, the *Gingko biloba,* which is regarded as a living fossil, because the majority of species in this division are extinct.

d) Gnetos such as *Welwitschia* sp. restricted to deserts in Namibia and Angola.

Figure 3.26 A photo of cypress tree among the popular Christmas tree

Source: *TAFORI, 2019*

Species belonging to this division are evolutionarily, more advanced than pteridophytes. They have more advanced vascular tissues, and they do not require water for fertilization. The presence of a highly reduced gametophyte and seed formation also makes them evolutionarily more advanced than ferns. Coniferophytes are very abundant in the cold and moist regions such as the southern highlands and along the slopes of Mount Kilimanjaro in Tanzania. Globally, coniferophytes are common in the North-western part of the United States, the northern hemisphere, and China.

Characteristics of division Coniferophyta

a) They are non-flowering, seed bearing plants, producing naked seeds which are not enclosed in ovaries or fruit tissues.

b) Sexual reproduction involves microspores (male gametophyte) and megaspores (female gametophyte) which are found in male and female cones or strobili respectively.

c) Fertilisation does not require water; instead, they develop pollen tubes which carry sperms to the ovule for fertilisation.

d) They have poor xylem with only tracheids as conducting elements but no vessel elements. This is the reason why most coniferophytes produce soft wood.

e) Their phloem tissues lack companion cells; instead, they are associated with albuminous cells.

f) Leaves are reduced into spiny or needle-like leaves to minimize water loss through transpiration. Exceptions are Gingkos and Cycads.

Distinctive features of division Coniferophyta

Presence of the following features in members of division Coniferophyta differentiate them from members of other divisions:

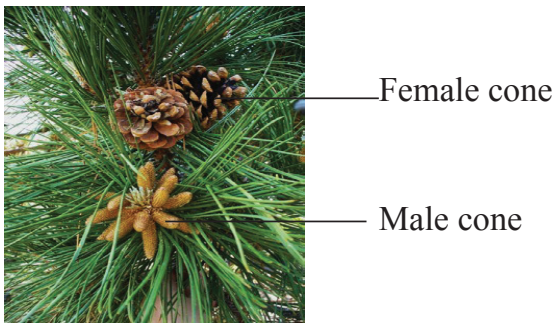
a) The plants bear cones from which microspores (pollen grains) and megaspores (ovules) are produced.
b) The pollen grains are winged to provide buoyance, hence they are wind pollinated.
c) They have seeds which are not enclosed within the ovary; thus, no ovaries, and no formation of fruits.
d) Their xylem lacks vessel elements but has only tracheids as the conducting elements.
e) Their phloem tissues are associated with albuminous cells instead of companion cells.
f) The majority produce resin in special ducts called resin canals. Such resin is useful in wound healing and deterring browsers.
g) Most are evergreen plants with needle-like shaped leaves.

Structure of *Pinus*

The sporophyte consists of roots, stem and branches, bearing needle-shaped leaves which appear in clusters of two to five. These clusters are called fascicle. Their leaves are dark green with cuticle, sunken stomata, and resin canals in the mesophyll. Their stems develop relatively wider annual rings of the xylem. The constituent tissues of these species have resin canals which run vertically and laterally along the stem. The bark, has secondary phloem, which is relatively thick and does not have companion cells, but albuminous cells that perform the same function as the companion cells.

The trunk has a tap root system with lateral roots in different directions. Roots of some *Pinus* form symbiotic association (mycorrhizae) with fungi. Young shoots have two types of leaves; small scaly leaves on the main stem and leaves on the dwarf shoots. In addition, the plant has foliar spars which develop into normal branches. The fertile plant bears female and male reproductive cones which are distinct when mature. The male cones are relatively soft or herbaceous and small while female cones are woody and relatively larger. Usually, male cones are borne on the lower branches while female cones are borne on the upper branches (Figure 3.27(b)). The leaves enclosing the cones are called sporophylls. For instance, microsporophylls are associated with male cones, whereas megasporophylls are associated with female cones.

(a)



(b)

Figure 3.27 General structure of (a) female cone and seeds and (b) *Pinus* plant

Reproduction of *Pinus*

The sporophyte generation is dominant, more pronounced, and varies in form or habit. They include shrubs and trees, consisting of roots, stems and leaves-bearing branches. The gametophyte is highly reduced (only a few cells). They are heterosporous, producing microspores which are pollen grains (male gametophyte) and megaspores (female gametophyte). Male cones bear microsporangium with microsporocyte which produce microspores by meiotic division, which give rise to light winged pollen grains (microspores). The nucleus within the pollen grain divides mitotically to form a pollen tube nucleus and a generative nucleus which later divides by mitosis to form two sperm nuclei. These pollen grains are transferred to mature female cones, mainly through the process called pollination.

Once the pollen grain has landed on the female cones, the pollen tube is formed and grows, carrying two male sperms to the archegonium and penetrate the ovule via a small hole called micropyle. In female cones inside the ovule, the megasporocyte produces four haploid nuclei through meiotic division. One of these cells develops into megaspore. The nucleus of megaspore undergoes mitotic division to form a small female gametophyte where by two or three archegonia are present; each with one egg cell. During fertilisation one of the sperms fertilises the egg to form a zygote while the other sperm degenerates. The zygote later develops to form a seed embryo which is a sporophyte in resting condition (Figure 3.28).

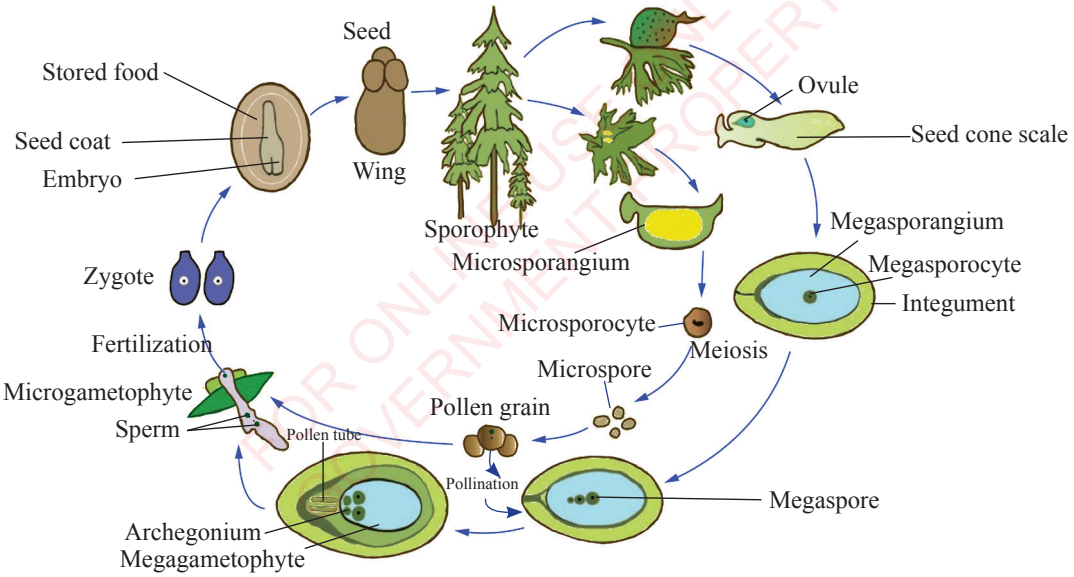


Figure 3.28 The life cycle of *Pinus* plant

Adaptations of *Pinus* to its mode of life

Pinus are able to adapt to their environment due to presence of the following features:

a) The root and shoot systems are well developed to provide the plant with a good contact to the soil and atmosphere.

b) They have roots for absorption of water and nutrients from the soil.

c) The plant has mechanical tissues for support and vascular tissues for transportation of water and food.

d) They have an elaborate mechanism for reducing water loss through transpiration. This becomes possible due to presence of thick cuticle, needle-like leaves to reduce their surface area and a reduced number of stomata pores. Additionally, their bark is coated with waxy material called suberin to reduce water loss.

e) They produce lighter pollen grains, each with two wing-like structures which make them to float in air, hence easily to be carried by wind for pollination.

f) They can reproduce sexually without necessity of using water, because the transfer of male gametes to female gametes is through pollen tube, which ensures reproduction in terrestrial environment where water is limited.

g) The seeds are winged; hence, they can be easily dispersed by wind.

Activity 3.8 Observation of *Pinus* sporophyte and reproductive structures

Materials

Branches of pine (*Pinus)* plants with male and female cones, hand lens or microscope.

Procedure

a) You are provided with branches of the *Pinus* species, with male and female cones. Examine the mature female cones which are relatively woody. At the base of each cone are two winged seeds; however, they might sometimes be missing, because they fall off when mature, especially if the cones are disturbed by wind or any other mechanical force. If seeds are missing, two small depressions, showing the mark of where the seeds were attached should be seen.

b) Carefully examine the male cones which are relatively small and much herbaceous compared to the woody female cones. Normally, male cones are borne in clusters at the axils of lower branches. Take some pollen grains from the male cones and mount a few in a drop of water on a slide for examination under the light microscope to observe the wings on each.

Questions

1. Draw a diagram of the male and female cones.
2. Draw a diagram of the pine pollen grain and show the wings.

Exercise 3.13

1. Outline ways in which coniferophytes are advanced compared to filicinophytes.
2. Explain the distinctive features of gymnosperms.
3. Explain the importance of wind in the life cycle of coniferophytes.

3.6.4 Division Angiospermophyta

Angiospermophytes are flowering plants which are the most advanced and adapted to terrestrial life. The word *angiosperm* is a combination of two Greek words; *Angeion* which means 'vessels' or 'carpels' and *sperma* which means 'seeds.' They produce seeds enclosed in the ovary, which later matures to become a fruit. Thus, their fruit is a mature ovary and the seeds in it are fertilized ovules. Angiosperms resemble coniferophyta in many aspects such as the ability to produce seeds. However, the presence of flowers and seeds enclosed in the fruit makes them distinct. Flowers and fruits have contributed significantly to the success of angiosperms in their ecosystems. Flowers are diverse in colour, aroma and morphology. These have made it easy to attract different pollinators, instead of relying solely on the wind. The ability to produce seeds enclosed in the fruit is also an adaptation to seeds' dispersal by animals which feed on such fruits.

The number of angiosperm species is over 257,000, existing in various sizes, shapes and forms, such as grasses, herbs, shrubs, vines, liana, suffrutescents and trees. Some of these plant species such as *Cassytha filiformis* are parasitic, hence they rely on other plants. Others grow as epiphytes on other plants without causing any harm. Angiosperms are the dominant plants in all habitats, ranging from terrestrial to aquatic environments, where plants such as water lilies and sea grasses are abundant. Based on duration, flowering plants are classified as annual, biannual or perennial. Annual plants are normally herbs and grasses that live only in one season. Biannual plant live for two seasons growing vegetatively in the first season and flowering in the second season.

Perennial plants live for three or more seasons. Example of perennial plants are trees. The angiosperm sporophyte is dominant with gametophytes entirely confined in it. The sporophyte consists of roots, the stem, branches, and leaves. The gametophyte generation is represented only by flowers in which the male and female gametophytes are confined. They have well developed vascular tissues with xylem containing tracheids and vessels which make the angiosperm wood harder than those of coniferophytes. The phloem on the other hand contains companion cells and sieve tubes.

Angiosperms are heterosporous. They produce microspores (male gametophyte) and megaspores (female gametophyte). Actually, the male gametophyte is the germinated pollen grain which is highly reduced into three nuclei, namely two male nuclei and a pollen tube nucleus. Whereas, the female gametophyte is found in the ovule's embryo sac; the ovary is reduced into

eight nuclei, namely three antipodal nuclei, two polar nuclei, and an egg contained between two nuclei called synergids (Figure 3.29). Following pollination, the pollen grain on the stigma develops a pollen tube carrying two sperm nuclei which grow down to the embryo sac via micropyle. One of the sperms fertilizes a haploid egg to form a zygote which later develops to form an embryo. The second sperm fertilizes the two polar nuclei forming triploid nutritive tissue called endosperm. This process is called double fertilization, because fertilization occurs twice. A fertilized ovule becomes a seed surrounded by two integuments (seed coat) and the ovary develops into a fruit.

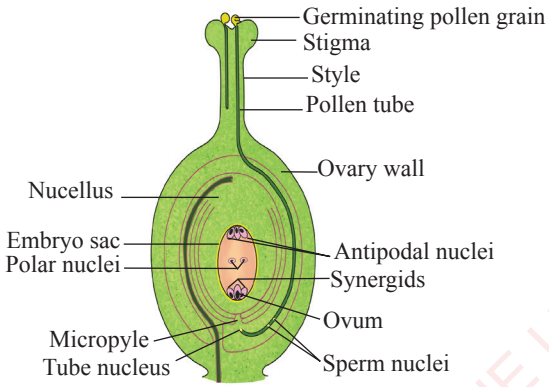


Figure 3.29 An ovary

Classes of division Angiospermophyta

Old system of classification recognised two classes based on the number of cotyledons; Monocotyledon and Dicotyledon.

Class Monocotyledoneae, such as maize, grass, millet, and sugar cane plants. Class Dicotyledoneae, such as bean plant, mango, and orange plants.

A recent estimate of the number of flowering plant species globally is approximately 400,000, distributed into about 393 families. When partitioned into their old two broad classes, a larger number of species are dicots, represented by 336 families. In contrast, monocots are represented by about 57 families.

Distinctive features of class Monocotyledoneae

The following features possessed by members of the class Monocotyledoneae (Figure 3.30) differentiate them from those of class Dicotyledoneae.

a) Leaf venation is parallel in monocots and the leaf blade or lamina is elongated with dorsal and ventral surfaces more or less identical.

b) The stem anatomy shows vascular bundles scattered in the ground tissue and closed as they lack vascular cambium, hence no secondary growth.

c) They have a fibrous root system which arises at the base of the stem replacing the primary root.

d) The monocot seed's embryo bears one cotyledon.

e) Flower parts are usually trimerous (in threes or multiple of threes).

f) Pollen grains in the monocots mostly have one aperture.

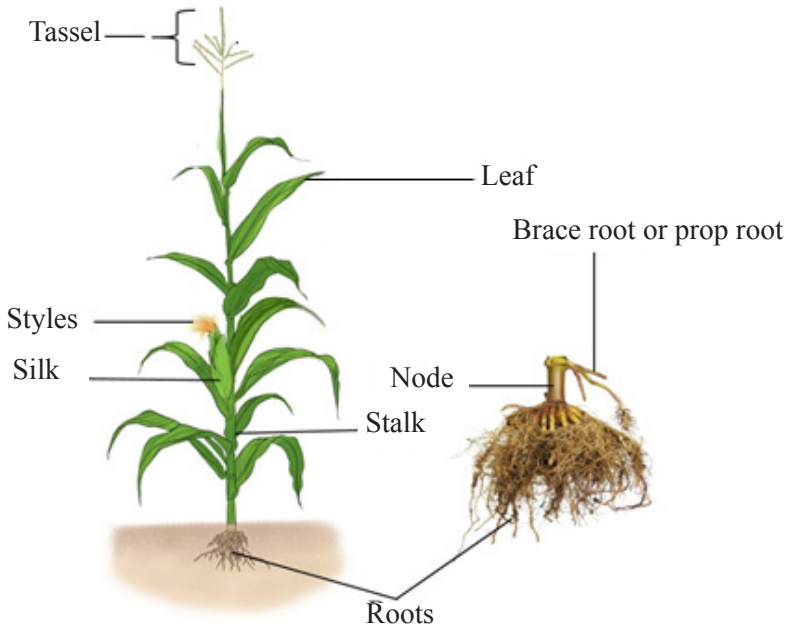


Figure 3.30 Structure of a monocot plant showing root and shoot systems

Distinctive features of class Dicotyledoneae

Members of the class Dicotyledoneae (Figure 3.31) differ from those of class Monocotyledoneae due to presence of the following features:

a) Dicot leaves have net like or reticulate venation with the dorsal and ventral surfaces of their leaf blade being distinct.

b) Their stems have vascular bundles which appear in a ring form. The vascular bundles are open, that is, they have a strip of cambium which gives rise to secondary growth.

c) The primary root system is a persistent and becomes thick tap root which develops lateral roots.

d) Their seed embryo has two cotyledons.

e) Floral parts are normally tetramerous or pentamerous (in four or five or multiples of four or five).

f) Pollen grains in dicots mostly have three apertures.

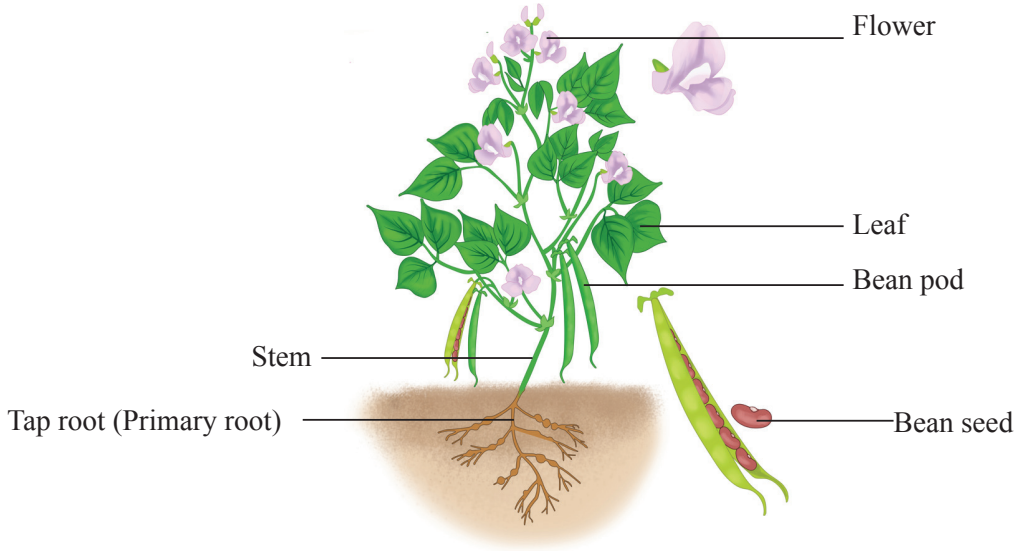


Figure 3.31 Structure of a dicot plant showing root and shoot systems

Activity 3.9 Observation of cross section of the stem and morphology of monocot and dicot plants

Materials

Monocot plant (grass or maize), dicot plant (beans *or Hibiscus*) plants with their flowers intact, light microscope, surgical or razor blade, and slides.

Procedure

a) Collect some monocot and dicot plants with their flowers from the school environment. Make sure that you uproot the entire plant carefully in order to display their root system clearly.

b) Observe the morphological structure of the two classes of plants collected.

c) Make a thin cross section of the stem of monocot and dicot plants. Place them on slides and observe one at a time using light microscope.

Questions

1. Summarise in a tabular form the morphological differences between the two classes of the collected plants.
2. Draw and label each of the two plants to display their root system, stem, leaf venation and flower(s).
3. Draw diagrams of the observed stem sections, indicating the vascular bundles.
4. What are the differences between the stem sections observed in (c)?

Safety precautions

1. Handle with care sharp objects like surgical or razor blade to avoid cutting your fingers or hands.
2. Be aware of some dangerous animals such as piercing insects and snakes while collecting monocot and dicot plants.

Structure of the flower

A flower is interpreted as a modified leaf of a plant which is highly specialised for reproduction (Figure 3.32). It can be bisexual or unisexual, depending on a plant species. Bisexual and unisexual flowers are called complete and incomplete flowers respectively. Flowers have the following major parts:

a) Receptacle

This is a swollen tip of a pedicel on which all floral parts are borne or attached. It has limited growth, which ceases as the last floral part is formed. The receptacle varies in shapes between members of one species and another. The floral parts are arranged in whorls around the receptacle, as rings of calyx, corolla, androecium and gynoecium. When all these whorls are present, the flower is termed as a perfect or complete flower, example, and flowers of cherries, roses, and orchids. In contrast, when one of the four whorls is missing, the flower is termed as incomplete flower. Examples include; flowers of sweet corn and most grasses. The floral parts are inserted in the following order from the base to the apex of receptacle; the first whorl is for the calyx, the second whorl is for corolla, the third whorl is for androecium, and the fourth whorl is for gynoecium.

b) Sepals

These are the lowermost or outermost structure, which are usually green, leaf-like in structure, protecting the developing flower whilst the flower is still a bud. As the inner parts of the flower grow and expand, sepals are pushed outwards. In some instances, they may become expanded and brightly more coloured, like petals. Examples include the flowers of *Aloe* and *Tulipa* genera. They may be separate or fused into a single outer sheath collectively called calyx.

c) Petals

These are normally located inside and above the sepals, are brightly coloured and expand to form the most conspicuous part of the flower. As such, they serve to attract pollinators such as insects and birds, which are essential for accomplishing the reproductive process. The petals may be separate or united in a single tube or united in several groups. The collective term for petals is corolla. In some flowers, both calyx and corolla are united to give a structure termed as "Perianth."

d) Androecium

This is a collective term for the male part of the flower, and includes anther and filament. Anthers are usually bright orange or yellow in colour. The anther and filament together is termed stamen. The transverse section of the anther shows that it is made up of 2-4 pollen sacs containing pollen grains or microspores. The whole stamen can be regarded as microsporophyll bearing microsporangia. The fertile microsporangia are born as pollen sacs at the distal end of the filament. When mature, the pollen sac ruptures to release pollen grains (microspores or male gametophyte) which develop into male gametes.

e) Gynoecium

This refers to the female reproductive parts of the flower which consists of the stigma, style, and ovary. These three parts are collectively called pistil or carpel. Gynoecium shapes vary in different species as some have a single carpel or a

number of separate carpels, or a number of carpels fused in a variety of ways. The carpel is either single or united in a closed hollow container housing (ovary), with one or more ovules. The ovules which are enclosed within the ovary bear a peculiar characteristic of angiosperms. They contain an embryo sac in which the female gametophyte is found. The distal end of the ovary bears a prolonged structure known as style, which terminates in a sticky surface called stigma.

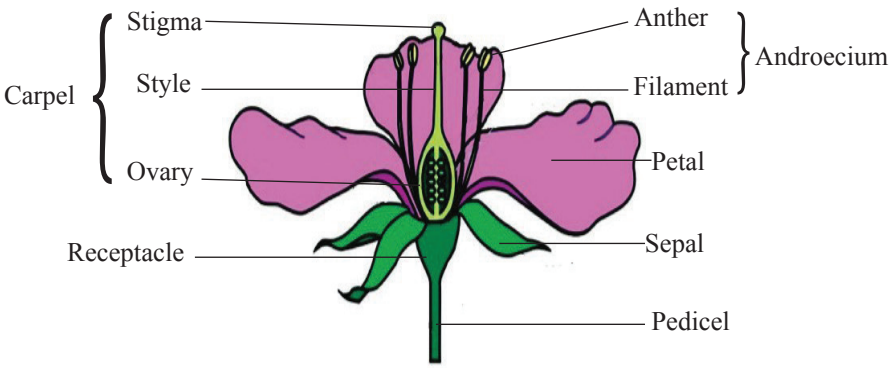


Figure 3.32 A generalized longitudinal section of an angiosperm flower

Flowers have the basic parts mentioned above, but morphological variations are common across plant species. These variations are based on the following attributes:

a) The manner of insertion of the parts.
b) The number of floral parts: Some flowers have all four whorls while others have less than four whorls.
c) The freedom or fusion of floral parts: Some parts in some flowers may be fused while other parts may not.
d) The relative position of the floral parts on the receptacle; may be above or below the receptacle.
e) The symmetry of the flower: some flowers have radial or bilateral symmetry while others are asymmetrical.
f) The distribution of the sexual parts within the flower: Some flowers have both gynoecium and androecium parts, while others have only one part.

Position of floral whorls at the receptacle

As pointed out earlier, the position of floral parts at the receptacle varies across the species. Based on the arrangement of the floral leaves at the receptacle in relation to the position of the ovary, three types of flowers are recognised:

a) Hypogynous flower

In this flower, the calyx, corolla, and androecium arise from the lower position of the ovary. This means that the calyx, corolla and androecium are inserted below the ovary that is the ovary is positioned above them. The ovary is therefore said to be superior as it occupies the highest position in the receptacle (Figure 3.33). Examples of hypogynous flowers include *Hibiscus*, tulip and tomato flowers.

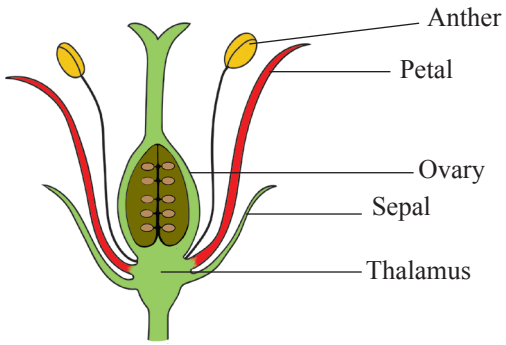


Figure 3.33 Structure of a hypogynous flower

b) Perigynous flower

In this type of a flower, the margins of the thalamus grow upwards to form a cup shaped structure called the calyx tube that encloses the ovary. However, it remains free from it, carries with it sepals and stamens, and the ovary is said to be half inferior. Examples include cherry and rose flowers. The term "perigynous" emanates from the nature in which other floral parts appear to enclose the ovary (Figure 3.34).

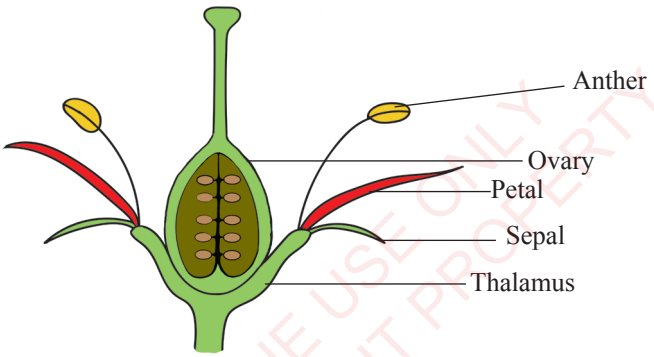


Figure 3.34 Structure of a perigynous flower

c) Epigynous flower

In this flower, the calyx, corolla, and androecium arise above the ovary and completely enclose it. The ovary is therefore said to be inferior, while the rest of the floral parts are said to be superior (Figure 3.35). Examples of epigynous flowers include the cucumber, apple, guava, and passion flowers.

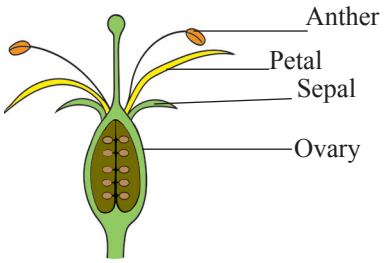


Figure 3.35 Structure of an epigynous flower

Flower symmetry

A flower can be dissected longitudinally to expose its internal parts for clear examination. One of the fundamental aspects of a flower plan is its overall shape which is described as symmetry. A symmetrical flower is the one that can be divided along at least one plane in relation to perianth into two or more identical parts which are mirror image of each other. Although most flowers have a certain kind of symmetry, few flowers have no symmetry and are referred to as asymmetrical flowers. Three categories of flowers' symmetry are therefore recognized namely, radial symmetry or actinomorphic flower, bilateral symmetry or zygomorphic flower and asymmetric flower.

a) Radial symmetry

A flower is said to have a radial symmetry when it can be split vertically through the centre in any one of several planes to produce identical parts which are mirror images of each other. This type of symmetry applies when each part of the whorl is identical with all other parts. Normally each side can have one sepal and one petal. Radially symmetrical flowers are said to be regular or polysymetric or actinomorphic (Figure 3.36). Literally, actinomorphic means star like because the flower can be divided into three or more identical parts. Most flowers have actinomorphic symmetry, for instance the *Hibiscus* flower. The symbol used to denote this type of symmetry is ⊕.

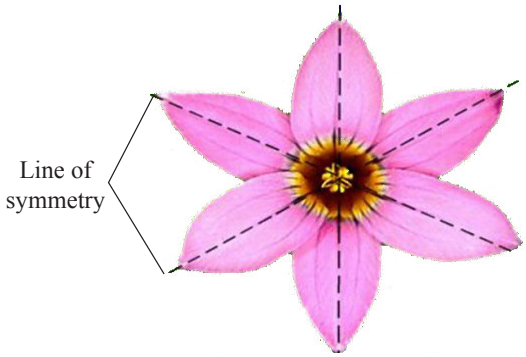


Figure 3.36 Structure of an actinomorphic flower

b) Bilateral symmetry

A flower is said to have bilateral symmetry when it can be split into two identical halves in one plane only. This type of symmetry is caused by differences in size and shape of petals and or sepals as can be noted in pea and bean flowers. Additionally, in some flowers, some whorls may be fused or some parts of an individual whorl may have different sizes compared to others in the same flower (Figure 3.37). Bilaterally symmetrical flowers are said to be irregular or zygomorphic. Example sweet pea. The symbol used to represent them is ●|●.

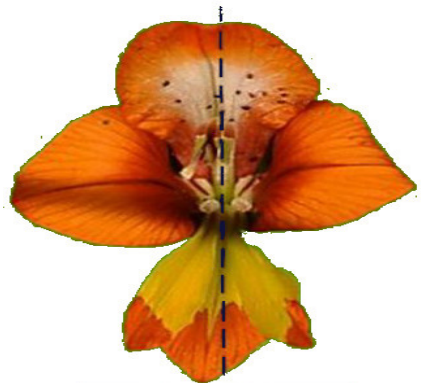


Figure 3.37 Zygomorphic flower

c) Asymmetric flowers

These flowers have no plane of symmetry, they cannot be divided into two equal halves in any plane; this is because their parts are spirally arranged, and good examples are flowers of *Cacti, Canna indica*, and ginger.

Methods of recording floral structure

Flower features can be represented to reveal the arrangement and relationship of the parts using three methods. These are a half-flower diagram, floral formula, and floral diagram.

A half flower diagram

This is a schematic representation of a flower cut longitudinally along the median plane in relation to the main stem to provide an elevation view of the flower. Normally, in regular flowers, cutting along this plane will result into two identical and opposite halves of the flower. A half cut flower diagram shows exactly how the floral parts are arranged in relation to each other (Figure 3.38a).

Floral diagrams

A floral diagram is a diagrammatic representation of the transverse section of a flower. It shows a plan of the flower as viewed from above with each of its floral whorls represented by a series of centric cycles showing their number, arrangement, relative position and fusion. The axis of the inflorescence is represented by a small cycle at the top of the diagram which is then regarded as the posterior position of the flower and bracts, if present. In principle, floral diagrams are never labelled, but standard symbols are used (Figure 3.38b). Although such symbols may not be representing physical structures, they carry additional floral information such as symmetry and orientation. Floral diagrams are useful in the identification of flowers, comparison of angiosperm taxa, reconstruction of fossil flowers and understanding the ontogeny and phylogeny of angiosperms.

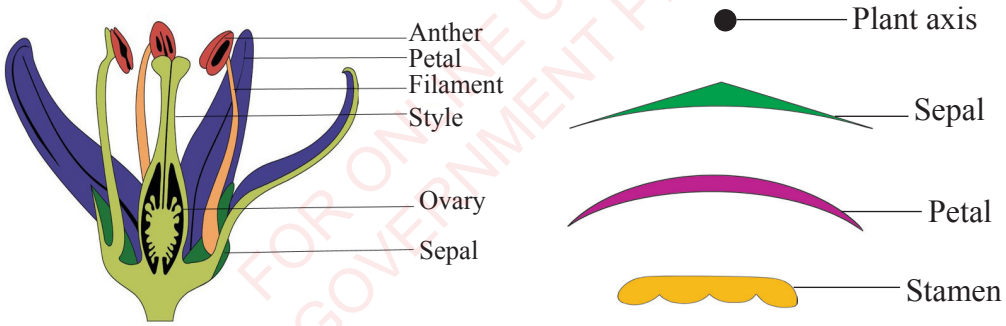


Figure 3.38 Representation of flower features (a) a half-flower diagram (b) floral symbols

Procedure for construction of a floral diagram

a) In drawing a floral diagram, it should be noted that different floral whorls are always represented in concentric circles starting with sepals on the outermost circle, followed by petals, stamens and carpels towards the inner side.

b) Examine mature floral buds and pluck them off the mother axis after noting the anterior and posterior sides.

c) The floral parts are drawn in a floral diagram, as they would appear in their transverse sections below the mother axis. A small circle is drawn above the floral diagram to designate the mother axis; however, for the terminal flowers, this circle is not shown.

d) In flowers associated with bracts (bracteate flower), a section of bract is drawn. In contrast in bracteolate flower; bracteoles are drawn in section on the left and right sides of the diagram.

e) The number of sepals and their arrangement in relation to the mother axis or aestivation are drawn in transverse sections. The odd number of sepals and petals are drawn either posterior or anterior to the flower (that is, opposite the mother axis or opposite the bract, respectively) with its sepals and petals alternating.

f) In zygomorphic flowers, sepals and petals with unequal sizes are drawn.

g) The spurred sepals or petals are shown by drawing a loop at their respective back.

h) The edges of fused sepals or petals are connected by lines.

i) The two lips of bilabiate calyx or corolla are joined by bulging lines.

j) In epipetalous flowers, where stamens are fused with petals, both whorls are linked with small radial lines.

k) Count the number of stamens; note their cohesion and adhesion to other floral parts and position in relation to petals, introse or extrose position; and draw them inside the petals in the floral diagram. Stamens are represented by transverse sections of anthers (Figure 3.39). Introse stamens face towards the centre while extrose ones face towards the petals. Staminodes are represented by an asterisk (*) or by a cross (x).

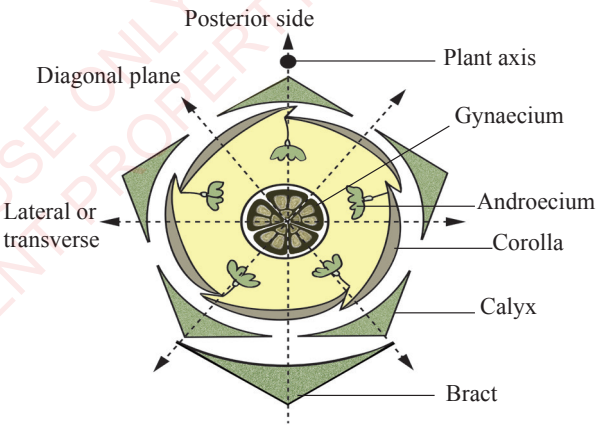


Figure 3.39 The floral diagram with labeled symbols

Floral formula

This is a representation of various floral parts using standardized symbols and numbers. It depicts floral information

pertaining to symmetry; floral whorls namely calyx, corolla, androecium and gynoecium; their numbers; and how they relate to each other. Symbols used in construction of floral formulae and their respective meanings are as summarised below:

⊕ Represents radially symmetrical flower (actinomorphic).

●|● Represents a flower with bilateral symmetry (zygomorphic).

♂ Represents unisexual male or staminate flower.

♀ Represents unisexual female or pistillate flower.

⚥ Represents bisexual (hermaphrodite) flower.

Br Represents flower with bracts (Bracteate).

Ebr Represents flower without bracts (ebracteate).

Brl Represents flower with bracteoles (Bracteolate).

K Represents calyx; each K is followed by a number indicating the number of sepals; for example K_5 represents five free sepals. If this number appears within brackets as in $K_{(5)}$, it denotes five fused sepals.

C Represents corolla; each C is followed by the number indicating number of petals for example C_5 depicts five free petals. If this number is enclosed by brackets as in $C_{(5)}$ it denotes five fused petals.

P Is used if sepals and petals are replaced by perianth. That is, calyx and corolla are fused and cannot be differentiated.

A Represents Androecium or stamens. The letter A is followed by the number of stamens like $A_{(5)+5}$ indicates a total of ten stamens in which five are free and five are fused. A_5 means five free stamens. If the stamens are attached to petals, their symbols are united with an arc line above them as in $C\overset{\frown}{A}$.

∞ Represents a large and variable number of whorls. It is used when the number is more than twelve in a flower. Example A_∞ means many free stamens and $A_{(\infty)}$ means many fused stamens.

G Denotes Gynoecium or pistil. Each G is followed by the number of carpels like G_1 or G_2, which means one carpel and two free carpels respectively. The carpels may also be fused as in $G_{(2)}$ or free as in G_4 implying two fused and four free carpels respectively. A small line under the letter $\underline{G}$ indicates superior ovary while a small line above it, such as $\bar{G}$, indicates an inferior ovary.

The following examples highlight how floral formula are constructed and interpreted.

⊕ ⚥ K_5, C_5, A_∞, G_5

The above formula indicates that the flower has radial symmetry, and it is bisexual. It further implies that the flower has five sepals, five petals, numerous stamens and five carpels. The flower has no bracts and all whorls are free from each other that is, not fused.

Floral formula of *Lathyrus* is;

$$\bullet|\bullet\ \varphi\ K_{(5)}, C_5, A_{(9)+1}, \underline{G}_1$$

Floral formular of *Ipomoea* is;

$$\oplus\ \varphi\ K_5, \overset{\frown}{C_{(5)}}, A_5, \underline{G}_{(2)}$$

The *Lathyrus* flower is zygomorphic, hermaphrodite, calyx with five fused sepals, corolla with five free petals, androecium with ten stamens (nine fused stamens and one free stamen); and a superior ovary with one free carpel.

The *Ipomoea* flower is actinomorphic, bisexual, calyx with five free sepals, corolla with five fused petals, androecium with five free stamens united with petals, and gynoecium is superior with two fused carpels.

Floral formulae and floral diagrams of a selected flower

The *Hibiscus* is a genus that belongs to the family Malvaceae (Figure 3.40). The genus is quite large, comprising of several hundred species that are native to warm temperate, subtropical and tropical regions throughout the world. Several species are widely cultivated as ornamental plants for their showy flower.

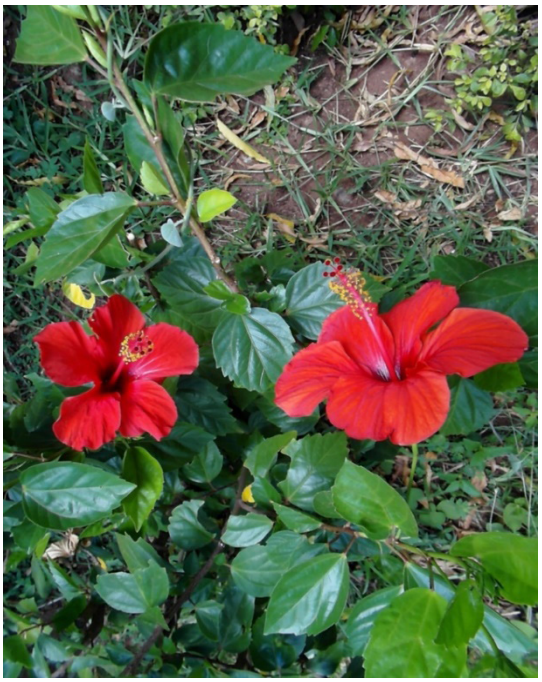


Figure 3.40 A photo of a common *Hibiscus* plant found in several places of Tanzania

The floral formula of *Hibiscus* flower derived from the individual with bracts (bracteate) and bracteoles (bracteolate), radial symmetry, bisexual, fused five sepals (calyx), free five petals (corolla) fused with infinite androecium, and five fused gynoecium (hypogynous).

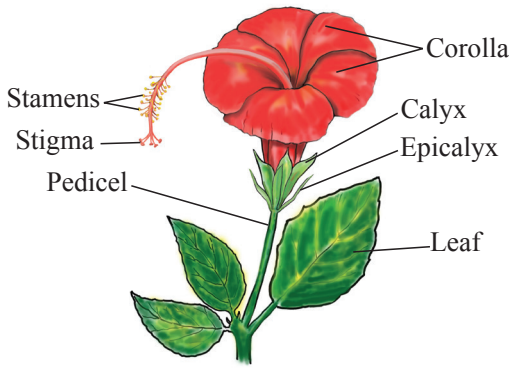
Floral formula of *Hibiscus*

$$Br., Brl.\oplus, \varphi, K_{(5)}, \overset{\frown}{C_5}, A_{(\infty)}, G_{(5)}$$

Floral diagram of *Hibiscus*

The schematic cross-section of *Hibiscus* flower is presented in structular form to express the arrangement of floral parts as projected in transverse or horizontal plane (Figure 3.41).

(a)



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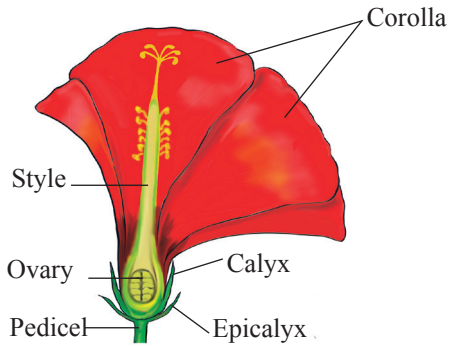


(c)

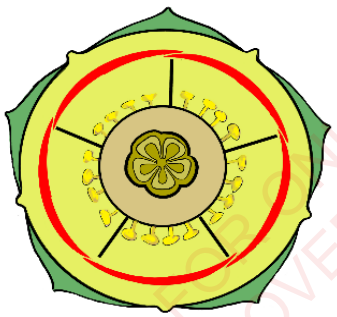


Figure 3.41 *Hibiscus* flower (a) vegetative morphology (b) half flower diagram (c) floral diagram

Activity 3.10 Observation and recording flower structures

Materials

Hibiscus flower, common bean flower, maize flower and elephant grass flower, hand lens, and surgical or razor blade.

Procedure

a) Collect two flowers from each of the following plants; *Hibiscus*, common bean, maize, and elephant grass.

b) Carefully observe each flower using a hand lens and state with evidence the classes to which each of the four plant species belongs.

c) Use a surgical or razor blade to make a transverse section of each flower and examine its parts.

d) Draw a transverse section of each flower and state their symmetry.

e) Prepare a longitudinal section of the second flower for each plant and draw well labelled diagrams.

f) Write the floral formulae of bean, elephant grass, and maize flowers.

g) From your observation, what features do the four flowers have in common?

h) Explain the main differences between *Hibiscus* and grass flowers

Safety precaution

Be careful when using surgical or razor blades.

Adaptation of Angiospermophytes to live on land

Angiosperms are the most recently evolved plants and are relatively the most adapted plants to terrestrial environment. Several factors have contributed to their survival, hence success on land; such factors include:

a) Flowers have contributed to the diversification of angiosperms throughout the time with adaptations to specialised pollination conditions. The adaptations exhibited by any given flower depend on the type of pollinators the flower is designed to attract, and have evolved features to enable pollinators to recognise and locate them quickly. For instance, bees can only see yellow, blue, and ultraviolet (UV) colors; therefore, bee pollinated flowers are yellow, blue or UV but not red. Butterflies detect red; accordingly, they can pollinate red flowers. Moths, which are nocturnal, pollinate brightly white coloured flowers, which can standout against darkness.

b) Most plants have ability to make and supply some food in the form of nectar and advertise their presence to the pollinators by producing fragrant scent. They also have a way of putting pollen on the pollinators and easily transferred to the flower of the next plant.

c) To ensure pollination, angiosperm-mophyte flowers have evolved ways of preventing non beneficial pollinators from visiting their flowers while embracing the beneficial pollinators. For instance, some flowers can be pollinated by insects with long proboscis or birds with long narrow beaks, only as they secrete nectar at the base of a narrow floral tube which is the right size of their corresponding pollinators.

d) Stamens have also become modified through time to prevent self-fertilisation in order to increase genetic diversity that will eventually enable them to inhabit a wider range of habitats. Additionally, closed carpel allows adaptations to specialised pollination conditions and controls self-fertilisation.

e) The male gametophyte in angiosperms is highly reduced into three nuclei (a tube nucleus and two sperm nuclei). This evolved to shorten the duration of time between pollination and fertilisation. Thus, unlike Coniferophytes, which takes about a year for fertilisation to take place after pollination, in angiospermophytes begins fertilisation soon after pollination, which translates into seed swift, seed formation, and species perpetuation.

f) Their male gametes are transferred through a special tube (pollen tube) to the female gametes for fertilisation. The ability to reproduce sexually without necessarily requiring water is an important feature in terrestrial environment, where water is limited.

g) Fruits produced by angiospermophytes are adaptations for dispersal by various agents such as wind, water, animals, and bursting. Animal dispersed

fruits have fleshy mesocarp which is edible or produces edible seeds or have various kinds of hooks. Wind dispersed fruits have structures for buoyancy, such as wings. These have provided angiosperms an opportunity to increase their domination in the terrestrial ecosystem.

h) Seeds produced by angiospermophytes have a highly nutritive tissue called endosperm, which provides food for the developing embryo, cotyledons, and sometimes, for the seedling when it first appears.

i) They have developed extensive root system for anchorage on land and absorption of water and mineral salts. Some plant roots have developed symbiotic relationship described as mycorrhizae with Fungi to increase the root surface area for absorption of nutrients and water from the soil.

j) They have an advanced and elaborated vascular system for transportation of materials. For example, xylem has both vessel and tracheids for efficient water movement.

k) They have stomatal pores for transpiration and gaseous exchange. These are modified in various ways to reduce excessive water loss.

l) Control of evapotranspiration, depending on the environment in which a particular species is adapted to live. For example, xerophytes have sunken stomata; most of them are restricted on the lower side.

m) They have cuticle, a thick waxy material covering the epidermal cells in all plant leaves. In addition, stems of monocots restrict excessive water loss.

n) Deciduous trees shed their leaves during dry season to reduce the rate of transpiration, hence, limiting water loss.

o) Asexual reproduction by vegetative propagation ensures rapid growth and maturity.

Economic importance of plants

Plants are very important to the survival of other organisms; without plants our day to day life would have been impossible. Animals' life is dependent on plants directly and or indirectly. However, there are some plants with detrimental effects to life of animals. The following are advantages and disadvantages of plants.

Advantages of kingdom Plantae

a) Species in this kingdom are the chief source of food for heterotrophs. Primary consumers such as browsers and grazers depend on angiospermophytes as their sole source of food. Likewise, human beings obtain various types of food such as vegetables, potatoes, sugar, cereals, and fruits from plants.

b) They are important atmospheric purifiers due to their ability to sequester carbon dioxide (CO_2), thus reducing its concentration in the atmosphere. Carbon dioxide is one of the greenhouse gases; hence its reduction in the atmosphere will in turn reduce the risks of global warming. Through photosynthesis, plants produce oxygen which is used by most of the organisms for respiration.

c) Plants such as legumes have symbiotic relationship with nitrogen fixing bacteria in their root nodules. These bacteria are capable of fixing unavailable nitrogen from the atmosphere into available forms, which can be absorbed by plants.

d) They help to conserve water in the soil by preventing excessive evaporation. For example, plant leaves and grasses are used as mulching materials covering the soil surface to conserve water.

e) Grasses and some trees have important catchment value, because they have matted root networks that reduce lateral flow of water, evaporation, and soil erosion.

f) Plant communities or vegetation such as grasslands, woodland, and forests provide habitats for wild animals. Additionally, bird species use plant materials for construction of their nests.

g) They are used in research and biological studies.

h) Plants are sources of traditional fuel such as charcoal and firewood. In Africa, for instance, approximately 90% of the population use charcoal as a source of domestic energy.

i) Ferns and most Angiospermophytes are grown as ornamental plants for indoor and outdoor decoration, examples: true ferns, *Hibiscus*, cacti and roses.

j) They provide raw materials for industrial purposes. Examples are cotton for making clothes, latex for making rubber, cellulose for making fiber products such as ropes, and wood pulp for making paper. Additionally, fibres from plants such as sisal are used to manufacture mattresses and carpets. White pines are extensively used for making boxes, furniture, floor, and panel.

k) Resins from pines are used for making premier paints and varnish solvents ointments, wax, and shoe polish.

l) They provide timber for various purposes such as furniture making, poles for houses construction and electric supply.

m) Forests attract tourists and thus aid in generating national income.

n) Plant leaves such as grass, banana and coconut leaves, are used in thatching houses.

o) Fern rhizome, root bark, and rhizome bark of certain species are used for growing Orchids.

p) Some plants are source of medicine for example Neem trees

Disadvantages of kingdom Plantae

a) Some plants can produce metabolites or accumulate toxic or poisonous products which are dangerous to consumers (animals). Cassava plants can accumulate cyanide, which is toxic, if consumed by humans. *Jatropha curcas* produces a toxic protein called curcin. Tea and coffee produce caffeine which in high doses may cause hypertension in humans.

b) Weed plants compete with food crops, leading into low crop yield.

c) Some plants are parasites to other

plant species. For instance, *Cassytha filiformis* is a parasitic weed in crops such as mango, orange and cashewnut trees; they cause serious crop loss and, consequently income loss.

d) Some aquatic weeds can colonise water bodies and affect ecosystem as well as hindering fishing and boating activities.

Exercise 1.14

1. Describe the distinctive features of the kingdom Plantae.
2. With the aid of diagrams illustrate the differences between the two classes of flowering plants.
3. Outline the distinctive features of the division Angiospermophyta.
4. With the aid of a well labelled diagram, describe the structure of a flower.
5. Briefly explain how *Hibiscus* flower is adapted to cross pollination.

3.7 Kingdom Animalia

Animals are a diverse group of organisms that make up the kingdom Animalia. This kingdom comprises of animals, which are multicellular eukaryotic organisms. Most of them have high level of tissue differentiation and specialised body organs. They undergo heterotrophic mode of nutrition; that is, they depend on other organisms directly or indirectly to obtain organic food. They digest food internally, particularly in the gut and store carbohydrate in the form of glycogen. Animals are mobile, they can move from one place to another in search for food, shelter, mates, and safety. Mobility in animals include movement of organs. For example corals are sedentary animals but their organs move to trap food. In most animals, body activities and responses are coordinated by the nervous and endocrine systems. Higher animals reproduce sexually, involving haploid gametes. Most animals are triploblastic organisms, meaning they have three body layers (outer layer; an ectoderm, middle layer; mesoderm, and endoderm as an inner layer); Examples of such animals include all multicellular animals, with the exception of certain invertebrates such as the cnidarians and sponges. Some are diploblastic, consisting of two layers of cells (ectoderm and endoderm); for example cnidarians (jellyfish, corals and sea anemones). Their body symmetry is bilateral, except phylum cnidaria that have radial symmetry and phylum, Porifera example sponges whose body regularly lack symmetry. Most animals have anterior and posterior ends, with oral and anal openings.

Kingdom Animalia is divided into about twenty eight phyla including Polifera, Cnidaria, Platyhelminthes, Nematoda, Annelida, Arthropoda, Mollusca, Echnodermata, Chordata and other smaller phyla. The first eight phyla fall under the group of invertebrates (animals without a backbone) while the ninth phylum, Chordata, includes some invertebrates and vertebrates (animals having a backbone). This book will deal with five selected phyla, namely Platyhelminthes, Nematoda (Aschelminthes), Annelida, Arthropoda, and Chordata.

3.7.1 Phylum Platyhelminthes

This is a group of flatworms. The worms can be free living or parasites. One of the best-known example of flatworms is the tapeworm.

General Characteristics of phylum Platyhelminthes

a) They are dorsoventrally flattened and some are unsegmented worms. Most of them have mouth and gut with no anus.

b) They have flame cells in the mesoderm for excretion and osmoregulation.

c) They are hermaphrodites with a complex reproductive system, which prevents self-fertilisation, but favours cross-fertilization.

d) They are triploblastic acoelomate animals, which have three body layers (ectoderm, endoderm, and mesoderm) without a body cavity or coelom.

e) Some have cilia on their outer surface for locomotion, for example Planaria, others have cilia in larval stage, for example miracidium larva in flukes, but lack cilia in adult stage.

f) They exhibit bilateral symmetry.

g) They have a very simple nervous system, with two nerve cords which run down on either side of the body. They have two simple brains called ganglia, which are simple bundles of nerves.

h) Some have two eyespots that help in sensing the presence of light.

i) Some platyhelminths have hooks and suckers for attachment. Examples of platyhelminths are *Taenia solium, Taenia saginata* (tapeworms), and *Fasciola hepatica* (liver fluke). Most members of this phylum are parasites while others are free living, for example: Planaria.

Classification of Platyhelminthes

Common Platyhelminthes, fall into three classes namely; class Cestoda, Trematoda and Turbellaria. Class Cestoda consists of endoparasite animals such as the tapeworms, including *Taenia solium* (the pork tapeworm), *Dipylidium caninum* (the dog tapeworm) and *Taenia saginata* (beef tapeworm). Class Trematoda comprises of the flukes; example, *Fasciola hepatica* (Liver fluke) and the blood flukes *Schistosoma haematobium* and *Schistosoma mansoni.* Class Turbellaria consists of the free living worms such as Planaria. They are flat worms.

Structure of a tapeworm

An adult tapeworm for example *Taenia,* consists of a knob-like head or scolex, equipped with hooks and suckers for attachment to the intestinal wall of the host; a neck region; and a series of flat, rectangular body segments (or proglottids), generated by the neck (Figure 3.42). The chain of proglottids may reach up to 15 or 20 ft (4.6–6.1 m) long. Terminal proglottids break off, and are egested in the feaces of the host. Nevertheless, the new ones are constantly formed at the neck of the worm. As long as the scolex and the neck are intact, the worm is alive and capable of growing. Rudimentary nervous and excretory systems run the length of the worm, through the proglottids. However, there is no digestive tract; the worm absorbs the

host's digested food through its cuticle or outer covering.

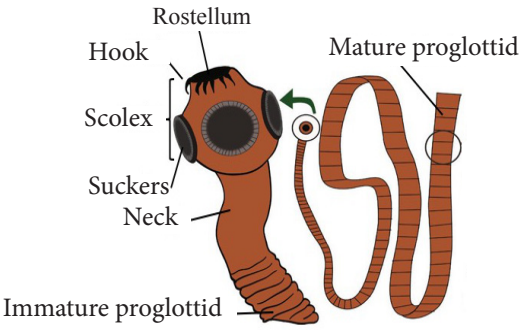


Figure 3.42 Structure of a *Taenia*

Adaptations of *Taenia* to its mode of life.
Taenia exhibits various special adaptations to its parasitic mode of life as follows:

a) It has scolex (head) with hooks and suckers for fixation and attachment on the host's gut wall

b) It lacks alimentary canal because it absorbs digested food materials from its hosts.

c) It has a thin and flattened body, which provides a large surface area for gaseous exchange and absorption of digested food.

d) Its body is covered by a living epidermal layer called the tegument which produces antienzymes to protect it from hosts' digestive enzymes.

e) It has a large number of ploglottids, which ensures production of a large number of eggs, hence high chance of survival.

f) It can respire anaerobically; therefore, it is able to live under low oxygen concentration, for example in the host's gut.

g) It is well adapted to osmotic pressure changes in the host's body.

h) It has flame cells, which collect excretory material from all parts of the body.

Structure of a liver fluke

Morphologically, an adult liver fluke, for example *Fasciola,* has a flattened leaf shaped appearance (Figure 3.43). In the anterior part, there is a triangular projection with a mouth surrounded by oral suckers at its apex. Ventrally, at the base of the projection, there are ventral suckers; and between the two types of suckers, there is a genital pore. Posteriorly, there is a minute excretory pore. The body is enclosed in a tough cuticle, which is extended into backward directed spines. Their muscle fibres have small glands with minute ducts. The mouth runs into the oesophagus which branches into two blind parts.

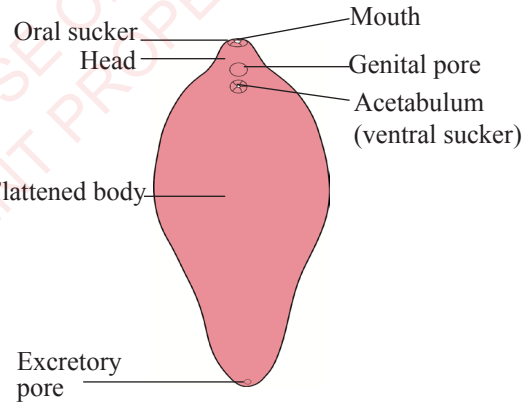


Figure 3.43 Structure of a liver fluke

Adaptations of the liver fluke to its mode of life

Liver fluke possesses the following features that facilitate a parasitic mode of its life in the host:

a) It has suckers that provide a means of attachment to the host.

b) It has tegument with spines that prevent it from being washed away by bile; and also help the parasite to erode liver cells.

c) The tough tegument and secretions from the glands prevent the worm from the effects of the host's toxins.

d) The parasite secretes enzymes that help it to penetrate the liver cells at various stages of its life cycle.

e) It has mechanisms and chemicals that suppress the actions of the host's digestive enzymes.

f) It has a high reproductive potential and different multiplication phases that balance its high mortality rate. They have two hosts, namely primary hosts (example: sheep and humans) and secondary host (example: fresh water snail called *Lymnea* sp.). They have several larval stages (miracidium, sporocyst, redia, cercaria and metacercaria) which increase the chances of survival and more perpetuation.

Economic importance of phylum Platyhelminthes

Some members of phylum Platyhelminthes play an important role in marine, freshwater and terrestrial ecosystems, while several species are harmful parasites to humans and other animals.

Advantages of phylum Platyhelminthes

a) Some species of Platyhelminthes feed on dead bodies of large organisms; therefore, they decompose organic matter in the soil; for example, free living Planaria.

b) Some members of Platyhelminthes are used in biological studies as specimens; for example, *Taenia* and *Fasciola.*

Disadvantages of phylum Platyhelminthes

Some members are parasites, which cause diseases to man and domestic animals. Examples include:

a) *Taenia* causes taeniasis; an intestinal tapeworm infection caused by eating raw or undercooked contaminated beef (*Taenia saginata*) or pork (*Taenia solium*).

b) *Fasciola hepatica* causes fascioliasis, which results into liver rot in sheep, cattle, and humans.

c) *Schistosoma haematobium* and *Schistosoma mansoni* cause urinary and interstinal bilharzia (schistosomiasis) respectively.

3.7.2 Phylum Nematoda (Aschelminthes)

Nematodes or round worms are the most numerous multicellular animals on earth, and inhabit a wide range of environments. Many of them are parasites of animals (including humans) and plants. They may cause serious diseases that are deleterious to human health and agricultural productivity. The free-living species inhabit marine and freshwater environments, as well as the soils and sediments of all of the various types of terrestrial biomes. Examples of Nematodes include: *Ascaris lumbricoides* (the pig and human nematodes), *Wuchereria bancrofti* (infecting human lymphatic system), hook worms (blood-feeding parasite of human and other animals) and *Meloidogyne incognita* (plant root knot nematode).

Structure of *Ascaris*

Ascaris are round, slender unsegmented worms with tapering bodies at both ends. They are characterised by being tubes within tubes, referring to the alimentary canal, which extends from the mouth on the anterior end to the anus, located near the tail (Figure 3.44). They possess digestive, nervous, excretory and reproductive systems, but they lack distinct circulatory and respiratory systems. The male and female *Ascaris* differ in morphology, as male is smaller and more curved at its posterior end than the female. They lack locomotory organs; movement is by undulating bodies in dorso-ventral waves.

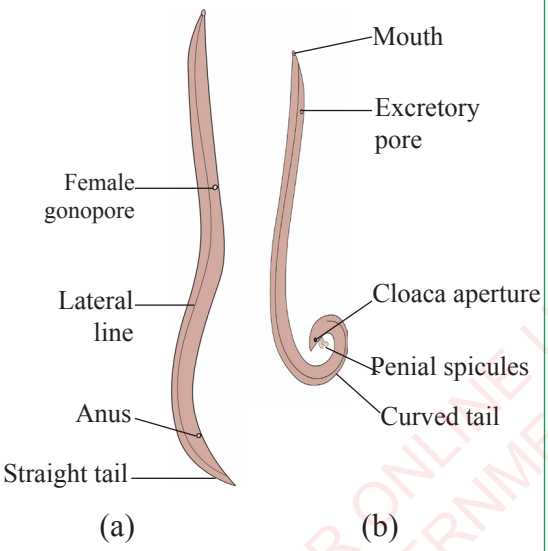


Figure 3.44 Structure of *Ascaris lumbricoides* (a) female and (b) male

Adaptations of *Ascaris* to its mode of life

Ascaris possesses some adaptive features that enable it to adapt to its parasitic mode of life. Thus:

a) It has a tough cuticle, which protects it from being digested by the enzymes of the alimentary canal of the host.

b) It produces chemicals, which act as anti-enzymes to the digestive enzymes of the host.

c) It has an alimentary canal, which opens at the mouth and anus. This enables the parasite to take food from the hosts' digestive system.

d) It possesses digestive enzymes in its digestive system for the completion of partially digested food from the hosts' alimentary canal.

e) It has sensory papillae around its mouth for detecting food present in the elementary canal of the host.

f) It respires anaerobically, and have low metabolic rate; hence, they are able to live inside the host's intestine.

g) It has high reproductive potential; thus, by producing large number of eggs, it ensures its survival and existence.

h) The pharynx has valves, which prevent regurgitation of the ingested food.

Economic importance of phylum Aschelminthes

Members of Aschelminthes are associated with both advantages and disadvantages as follows:

Advantages of phylum Aschelminthes

a) Nematodes, such as *Ascaris* are used in biological studies in different ways; for instance, in laboratory practical studies.

b) Some nematodes are used as biological control agents for pest insects. They attack insects and kill or hinder their development.

Disadvantages of the phylum Aschelminthes

Some Aschelminthes are parasites and cause diseases in plants and animals. Examples include:

a) *Wuchereria bancrofti* that causes elephantiasis. This disease infects the human lymphatic system by blocking it; resulting in the accumulation of the lymph in legs, hands, and/or scrotal sacs.

b) *Ascaris lumbricoides* causes ascariasis in humans that may lead to obstruction in the gut and anaemia.

c) *Meloidogyne incognita* causes root knot galls in plants that drain photosynthetic products; hence, affect plant growth and reduce yield.

3.7.3 Phylum Annelida

Members of this phylum are known as ringed or segmented worms. This is a large phylum comprising of lugworms, earthworms, and leeches. The species are adapted to various habitats; some members are aquatic, living in marine and fresh water, and others live in moist terrestrial environments.

Characteristics of phylum Annelida

a) They are triploblastic, coelomate organisms.

b) They have bilateral symmetry.

c) They are metamerically segmented.

d) They have a definite outer covering called cuticle

e) They have chitinous hair-like structures called chaetae (except in leeches), the chaetae of polychaetes are found on structures known as parapodia.

f) They have a lip like extension on the first segment above the mouth (prostomium).

g) They have nephridia as typical excretory organs.

h) They have central nervous system, with paired cerebral ganglia in which paired commissures around the gut lead to a double ventral nerve cord, expanded to form a ganglion in every segment.

Body plan of coelomates

In annelids and other coelomates there is an extensive internal space or body cavity called a coelom. This is the space between the body wall and the alimentary canal (Figure 3.45).

Functions of the coelom

The coelom has the following biological significance to an organism:

a) It contains coelomic fluid which acts as a hydrostatic skeleton. This is found in such organisms as earthworms.

b) It separates the alimentary canal from the body wall so that the functions of the two parts take place independently.

c) It allows the animal to grow larger.

d) The coelomic fluid may function as a circulatory medium for transportation of food, gases, and excretory wastes.

e) It provides space for enlargement of internal organs.

f) In some animals, it plays an osmoregulatory role.

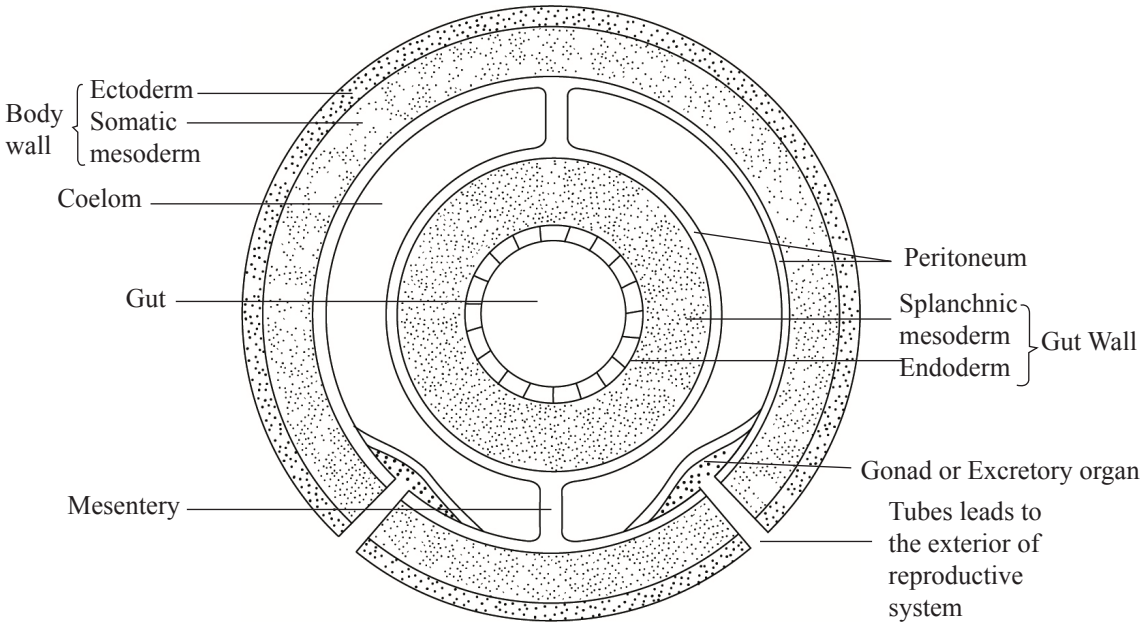


Figure 3.45 Transverse section of a generalised coelomate

Classes of phylum Annelida

The phylum has three classes namely: Class Polychaeta, which includes the marine bristle worms with many chaetae and parapodia, examples are *Nereis* (the ragworm) and *Arenicola* (the lugworm). Class Oligochaeta which includes; the earthworms and fresh water worms, that have few chaetae without parapodia, for example *Lumbricus* (the common earthworm), *Tubifex* (fresh water earthworm sometimes called sludge worm, or sewage worm). Another class of annelida is class Hirudinea which includes segmented worms with fixed number of segments, and have neither chaetae nor parapodia; an example is *Hirudo* (the leeches).

Structure of earthworm

An earthworm is an elongated, tube-shaped, metamerically segmented organism (Figure 3.46). Its digestive system runs through the length of its body. It has a thin wet skin through which gaseous exchange takes place. There is a double transport system composed of coelomic fluid that moves within the fluid-filled coelom. The circulatory system is simple and closed. The worm has a central and peripheral nervous systems. The central nervous system consists of two ganglia above the mouth, one on either side, connected to a nerve cord running back along its length to motor neurones and sensory cells in each segment. A large number of chemoreceptors are concentrated near its mouth. Circumferential and longitudinal muscles on the periphery of each segment enable the worm to move. Similar sets of muscles line the gut and their actions move the food towards the worm's anus.

Earthworm is a hermaphrodite, meaning that, the organism has both male and

female reproductive organs. Has an opening of spermotheca, which is found in segments 9, 10, and 11. Seminal fluid from another worm is passed through the opening during copulation. Ventrally, on segment 14, there are very small slits, which are openings of the oviducts (female opening) and on segment 15; there are openings of the vasa differentia (male opening). Additionally, earthworm has clitella (singular clitellum) which secret a cocoon in which eggs are deposited. The mouth is overhang by a flap called a prostomium. Movement is by means of paired chaetae.

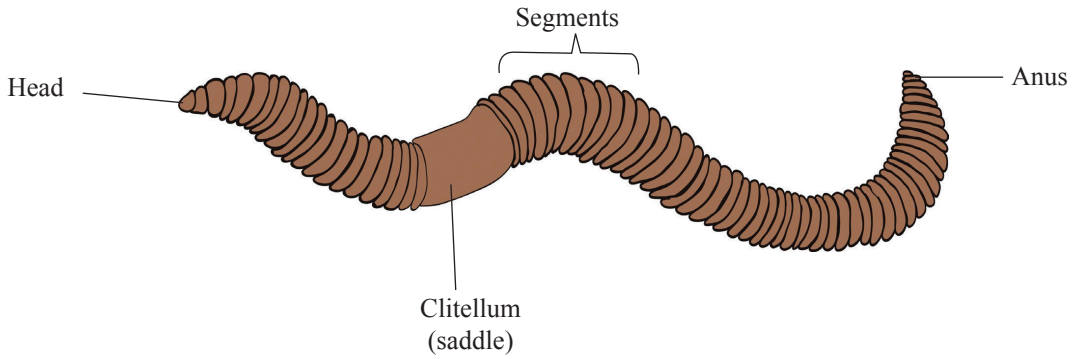


Figure 3.46 Structure of the earthworm

Adaptations of earthworm to its mode of life

a) They have ideal shapes with chaetae for burrowing.

b) They have gizzard for breaking up plant tissues.

c) They have clitellum, which holds together earthworms during copulation and forms an egg depositer structure called cocoon to ensure efficient provision of offspring during unfavourable conditions.

d) The mucus secreted helps to bind the walls of burrows and helps the worm to pass through smoothly.

e) They can thrust the earth aside when it is loose and consume it when it is tight. This ability ensures burrowing under both conditions.

f) They are omnivorous; as they feed on live plant matters, fungi, bacteria and microscopic animals. They also feed on dead organic matter from plants and animals. This feeding habit ensures sustainable food supply.

g) Under natural conditions, earthworms are less active; this limits oxygen consumption.

h) They have looped surface vessels, which facilitate absorption of oxygen over a short diffusion distance.

i) Their haemoglobin has high affinity to oxygen.

j) The head is less elaborate. The worm has tactile and photoreceptive cells for locating food at night and sensing light during the day respectively.

k) They have chaetae that are used for movement.

Economic importance of Annelids

Annelids are both ecologically and economically important; even though on the other side, they have some drawbacks.

Advantages of Annelids

a) They improve soil aeration, drainage channels and increase depth of the top soil through burrowing and mixing of soil layers.

b) They are used as bait in fishing industry, for example earthworms.

c) They are used as source of nutritious food rich in proteins and vitamins for fish and carnivorous birds.

d) They are ecological decomposers; hence, they contribute to nutrient circulation; since they feed on decaying organic matter.

e) They are used for removing soil pollutants from the soil and clean the environment by transforming organic wastes during feeding as a way of waste management.

f) Their excretory wastes in form of casts increase cementing effects of soil particles; hence, increase water-holding capacity.

g) They are used as specimens in biological studies.

Disadvantages of Annelids

a) They increase soil porosity and aeration, which is detrimental to paddy fields (rice plants in the field).

b) They damage young roots of the growing plants.

c) Leeches are harmful to mammals, reptiles, and fishes as they suck blood.

Activity 3.11

S_1 S_2 S_3

Figure 3.47 Specimens S_1, S_2, and S_3

Examine the external features of specimens S_1, S_2 and S_3, (Figure 3.47) and then answer the questions that follow.

1. Identify the specimens by their common names.
2. In what kind of habitat would you expect to find specimen S_3?
3. What are the observable features; which make specimens S_1, S_2 and S_3 differ from each other?
4. Name the phylum and classes to which each of the observed specimens belong.

3.7.4 Phylum Arthropoda

This is the largest group in the Kingdom Animalia, with high species diversity. Arthropods represent about three-quarters of all known living organisms. Some of the well- known arthropods include insects, crustaceans, and arachnids. Arthropoda comes from two Greek words *arthro* that means 'joint' and *podos* that means 'foot'. Therefore, all arthropods have jointed appendages. Arthropods are found in almost every known environment including marine, freshwater, and terrestrial ecosystems. They vary extremely in their habitats, life histories, and feeding habits.

Characteristics of phylum Arthropoda

a) They possess a chitinous and sometimes calcareous exoskeleton, which may be rigid, stiff or flexible; shed during growth in some organisms.
b) They have jointed, paired appendages such as legs and antennae.
c) They have segmented bodies, which are arranged into regions, called tagmata comprising of the head, thorax, and abdomen. The head of some arthropods such as arachnids and crustaceans is fused with the thorax to form a structure called cephalothorax (prosoma).
d) Their body plan is bilaterally symmetrical.
e) They have a ventral nervous system and open circulatory system, which is dorsally positioned.
f) They are triploblastic coelomate animals, which are metamerically segmented.
g) Their coelom is reduced and confined to cavities of excretory organs and reproductive ducts during their development and form another cavity called haemocoel.
h) They have an open circulatory system.

Classification of Arthropods

Arthropods are classified into five classes namely; class Crustacea, which include crabs, class Arachnida, which include spiders and scorpions, class Chilopoda, for example centipedes, class Diplopoda, for instance millipedes, and class Insecta, which include cockroaches and grasshoppers.

Class Crustacea

Crustaceans form a large group of arthropods that include familiar animals such as crabs, lobsters, prawns, shrimps, barnacles, and crayfish. Most crustaceans are marine aquatic animals, other are found in fresh water habitats, and a few are terrestrial,

for example woodlice (Isopota) found in leaf litter.

Distinctive features of class Crustacea

Crustacea have distinctive features that make them unique among other arthropods as highlighted below:

a) They possess two body division, which are cephalothorax (the head fused with thorax) and abdomen.

b) They have carapace or an exoskeleton hardened with calcium salts which acts as a protective shell.

c) They have heads bearing two pairs of antennae.

d) They have a pair of compound eyes at the ends of movable stalks.

e) They have at least three pairs of mouthparts.

f) Gills are used for gaseous exchange, which are the outgrowth of the body wall or limbs.

g) They have variable number of legs, sometimes up to ten legs and can be modified for swimming. Unlike other arthopods, the legs and other appendages of Crustacea have two branches (they are biramous).

Structure of a crab

A crab is covered with a thick exoskeleton (carapace) composed of calcium carbonate. This means they are well protected against predators (Figure 3.48). The body is divided into two parts: the cephalothorax and abdomen. The abdomen is entirely hidden under the carapace; it may not be visible at all, unless the crab is turned over. The head bears two pairs of antennae. The animal is equipped with a pair of claws (pincers) which are the most important weapons with at least three functions: seizing, eating and subduing the prey. If the food is a shellfish, then the pincers can exert force to open or break the mollusc's shell. Males also use pincers for or during fighting.

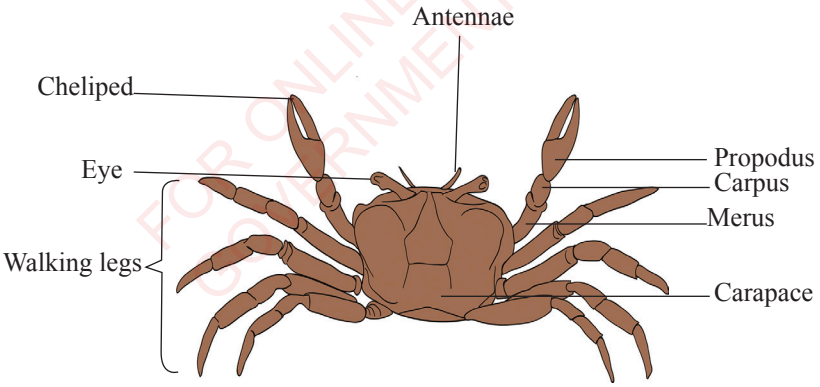


Figure 3.48 Structure of a crab

Class Arachnida

The arachnids represent the second largest group of terrestrial arthropods after the insects. The class includes the animals whose bodies are organised into two tagmata called cephalothorax or prosoma (fused head with thorax) and abdomen (opisthosoma). Most of them are carnivores, except the mites, which are herbivores. Members of this class include spiders, mites, ticks and scorpions.

Distinctive features of class Arachnida

Arachnids can be distinguished from other members of the phylum Arthropoda by the following features:

a) Their bodies are divided into two regions; prosoma and opisthosoma, separated by a narrow waist-like constriction.

b) They lack antennae; alternatively, they use pedipalps to detect external stimuli.

c) They lack compound eyes, they only have simple eyes.

d) They lack true mouthparts; instead, they have two pairs of appendages born from prosoma. One pair, the chelicerae or poisonous fangs, is used for killing preys or defending themselves; the other pair called pedipalps holds the prey in place when the animal injects poison.

e) Usually they have four pairs of walking legs.

f) Their respiratory structures are book lungs or book gills or trachea.

Structure of a spider

The spider has two main body parts: a fused head and thorax, called cephalothorax and abdomen (Figure 3.49). Most external appendages are attached to the cephalothorax. The appendages are legs, chelicerae, mouthparts, and pedipalps. On the ventral part of the abdomen are two hardened plates covering the book lungs. The spinnerets, which produce silk, are also located in the abdomen.

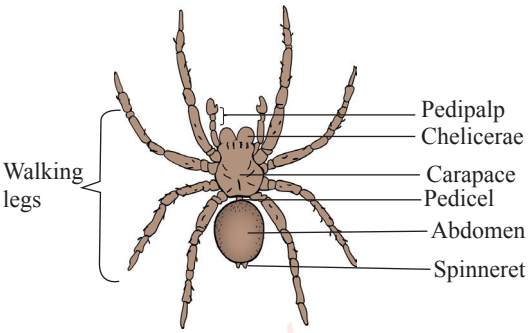


Figure 3.49 Structure of a spider

Adaptations of spider to its mode of life

Spiders live in almost every habitat. They are adapted to different environments because:

a) They have pairs of chericerae which produce silk for capturing preys.

b) They have pedipalps for sensation.

c) They have four pairs of legs for locomotion.The hairy spiders have stings used to paralyse prey and defend themselves.

Subphylum Uniramia

The centipedes (Chilopoda), millipedes (Diplopoda) and insects (Insecta) form a closely related group of arthropods.

They have three features that distinguish them from other arthropods. The first is possession of a single pair of antennae (crustaceans have two pairs and arachnids have none). The second is the presence of strictly uniramus (unbranched) appendages. Thirdly, the cuticle is hardened using tanning process involving chemicals known as hydroquinones. It is made waterproof using wax, and never has calcium carbonate. For these reasons, the three classes are nowadays grouped together under "Uniramia".

Class Chilopoda

This class consists of organisms found in terrestrial environment. They are terrestrial animals abundant in moist areas, such as leaf litters, under logs or rocks. An example of chilopoda are centipedes.

Distinctive features of class Chilopoda

The following features distinguish centipedes from other members of the phylum Arthropoda:

a) They have a flattened body with a distinct head. However, other body segments are similar, the trunk is not obviously divided into thorax and abdomen.

b) They have one pair of legs per segment.

c) They are carnivores, feeding mainly on insects and worms.

d) Their first trunk segments have appendages, which are modified into a pair of poisonous fangs.

Structure of centipede

Centipedes have a head bearing eyes, well-developed one pair of mouthparts (jaws), and one pair of antennae (Figure 3.50). The body consists of many segments, each of which bears one pair of legs. The legs of the first body segment are modified into poisonous claws, and are used for defence as well as for capturing and paralysing preys. They have tracheae used for gaseous exchange.

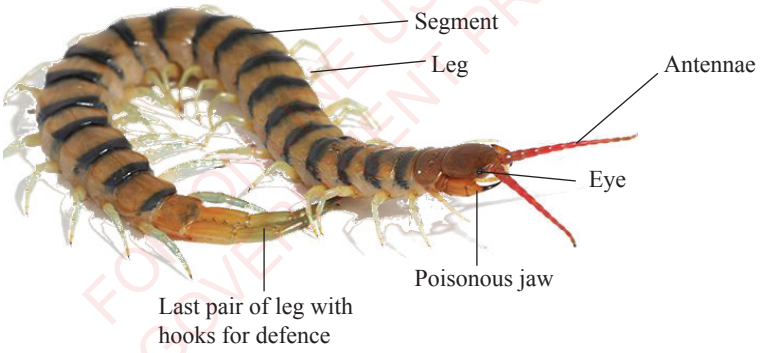


Figure 3.50 Structure of a centipede

Adaptations of the centipede to its mode of life

Centipedes are adapted to a wide range of habitats because:

a) They are fast moving animals; this helps them to catch their prey.

b) They feed on insects, spiders, and worms, which they hunt and paralyse with a bite of their poisonous claws.

c) They have antennae for sensation.
d) They have poisonous claws for defence and hunting.
e) They have legs for locomotion.
f) The last pair of legs has hooks for defence.

Class Diplopoda

The class Diplopoda consists of members with many legs; usually two pairs of legs per body segment. An example of a member of class Diplopoda is a millipede. The head bears one pair of antennae and a pair of mouthparts (jaws) while the trunk is not divided into thorax and abdomen. They are scavengers that feed on decaying organic matter, like leaves and compost.

Distinctive features of class Diplopoda

Diplopods have unique features, which differentiate them from other Arthropods.

a) They have round bodies with clearly defined head, followed by other similar segments.
b) They have many legs; with two pairs of legs per segment.
c) Most millipedes are herbivorous, feeding mainly on decaying vegetation.

Structure of millipede

The millipede has elongated and cylindrical body in which each body segment bears two pairs of legs. Millipedes are made up of a series of segments, whose number varies greatly from one species of millipedes to another (Figure 3.51). Many of the segments contain special glands that secrete a noxious chemical to repel predators. The first segment behind the head does not have legs, but the rest of the segments have legs. Towards the end, some of the segments have no legs. The number of legless segments varies from one millipede to another. Some species of millipedes have hair or spiny appendages protruding from their bodies. Its head is on one end of its body, and is about the same diameter as the adjacent segment. Also the head has a pair of antennae that helps the millipede to sense the surrounding environment. One pair of mouthparts (jaws) is on the front part of its head and the eyes are fixed above its jaws. Most millipedes have simple eyes that provide basic vision, but not all types or species of millipedes have eyes.

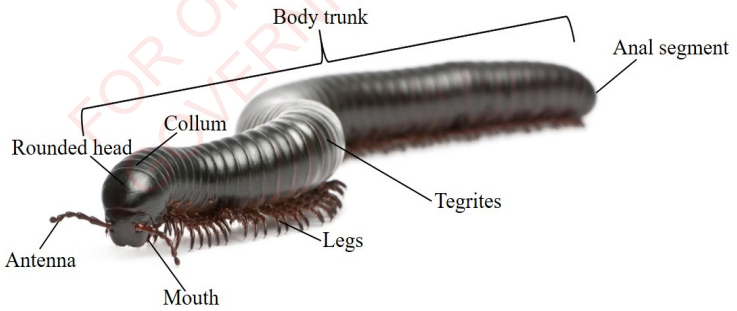


Figure 3.51 Structure of a millipede

Adaptations of the millipede to its mode of life

Millipedes have the following features that make them adapt to their environment:

a) They have many, short and strong legs that enable them to burrow into the soil.

b) They produce special secretions, which help them to moisturize dead organic matter on which they feed upon.

c) A millipede tends to curl up into a tight flat coil for self-defence, and protect their delicate legs inside an armoured exoskeleton.

d) Millipedes produce an offensively odorous fluid (repugnatorial fluid) when provoked, this acts as a defence against predators.

Class Insecta

The class contains all insects and is the most diverse group of organisms on earth. Members of this class are found in all environments including fresh water aquatic and terrestrial environments, but very few are found in marine habitats. They differ in morphology and feeding habits. Although members of this group vary greatly, they have some common characteristics, which make them to belong into the same class. Members of this class have three pairs of walking legs, three distinct body parts or regions and one pair of antennae borne on the head. The antennae are used as sense organs for detection of odour molecules in the air, changes in the concentration of water vapour, sounds, and gauging air speed. Examples of insects include grasshopper, butterfly, house fly, cockroach, beetle, bees, ant, wasp, and termite.

Activity 3.12

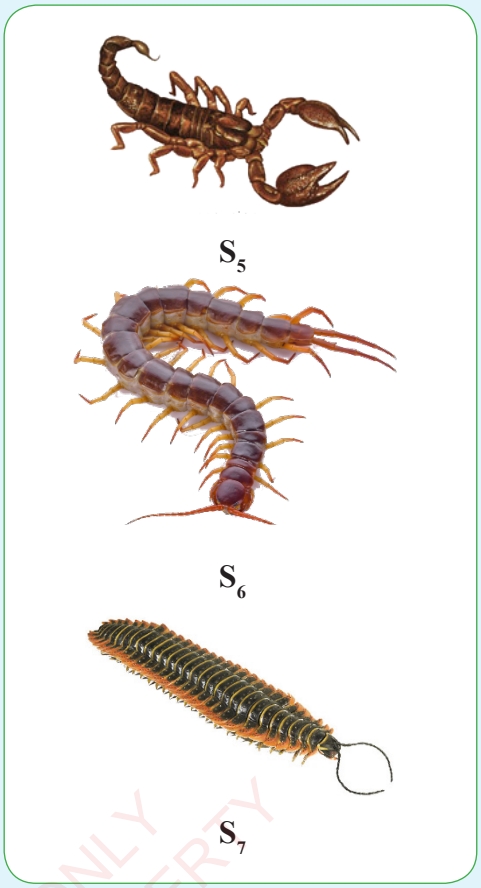


Figure 3.52 Specimens S_5, S_6, and S_7

Study specimen S_5, S_6, and S_7 (Figure 3.52) carefully, then answer the questions that follow:

1. Identify specimens S_5, S_6, and S_7 by their common names.
2. Name the classes to which specimens S_5 and S_6 belong.
3. List the observable features that have enabled you to place the two specimens in (2) above into their respective classes.

Distinctive features of class Insecta

Insects have the following features that differentiate them from other arthropods:

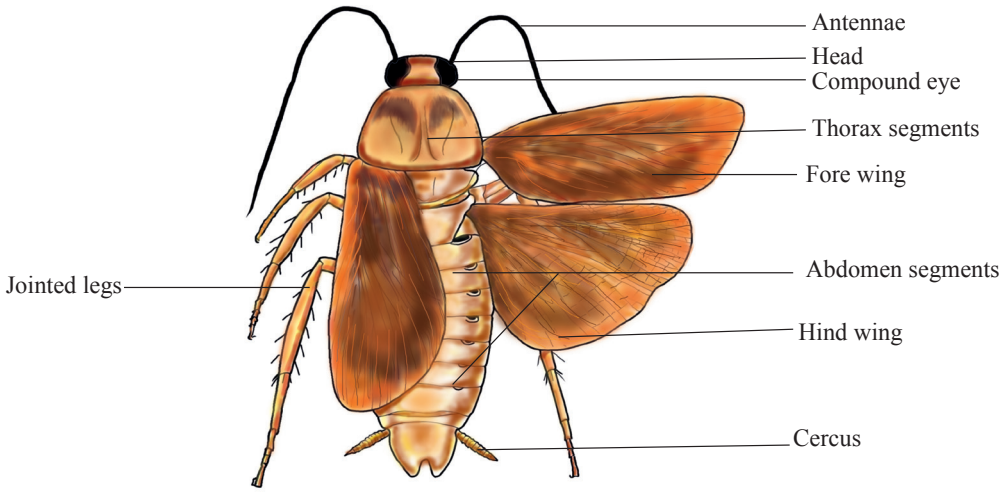
a) Their bodies are divided into three main regions or tagmata, namely the head, thorax, and abdomen.
b) They have three pairs of walking legs on the thorax (one pair per thoracic segment).
c) They usually have one or two pairs of wings on the thorax, some members may lack wings.
d) They use the tracheal system as their respiratory surface with segmental spiracles.
e) They undergo metamorphosis during their development through the molting process.
f) They have a pair of compound eyes and simple eyes.
g) They usually have three pairs of mouthparts, which are maxillae, mandible, and labrum.

Structure of a cockroach

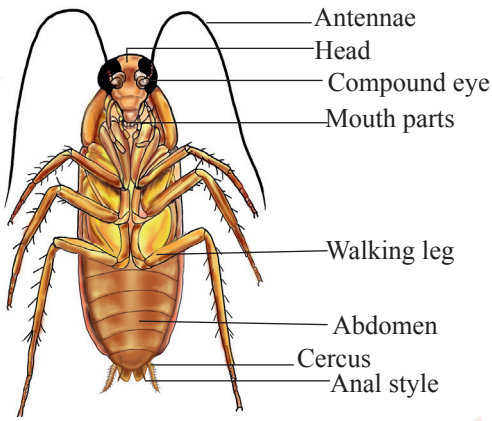
The body of a cockroach is elongated and segmented, divided into a head, thorax, and abdomen. The thorax is subdivided into three parts; prothorax, mesothorax and metathorax and each segment bears one pair of legs (prothoracic legs, mesothoracic legs and metathoracic legs respectively). The thorax also bears two pairs of wings in most adults insects. The body is covered by a rigid exoskeletons (cuticle) secreted by the epidermal layer. This occurs in jointed sections or plates to allow body movement. The exoskeleton is made up by a structural protein known as chitin. It is coated with wax, which is impermeable to water. The exoskeleton provides attachment for body muscles. Cockroaches are mostly dark brown or reddish in colour. Male cockroach has a narrow abdomen an expanded tergum of the last visible segment, and has a pair of styles at the end of abdomen, while the female cockroach has a wide abdomen with a large podical plates used to carry the ootheca, and lacks styles (Figure 3.53 a, b and c).

3.7.4 Body systems in arthropods

Like other animals, arthropods have various body systems which enable them to perform and sustain their life processes. These include: respiratory, circulatory, digestive, nervous, reproductive and excretory systems. In this text, digestive and reproductive systems will be dealt with.



(a)



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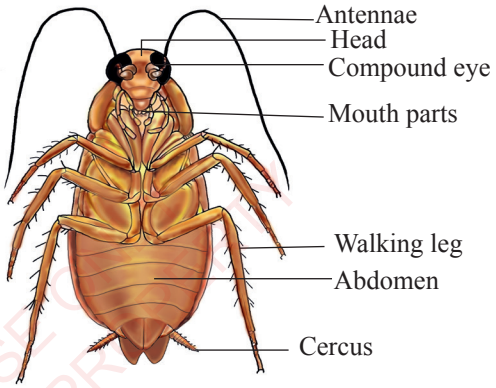


(c)

Figure 3.53 Structure of a cockroach (a) dorsal view (b) male ventral view (c) female ventral view

Digestive system of a cockroach

The alimentary canal of the cockroach is long and coiled tubular structure starting at the mouth opening. It is divided into three main parts, namely foregut (stomodaeum), midgut (mesenteron or ventriculus), and hindgut (proctodaeum). The foregut is differentiated into five parts: Buccal chamber, pharynx, oesophagus, crop, and gizzard. The fist two parts (buccal cavity and pharynx) are found inside the head capsule and not visible in the dissected cockroach, while the other three part are visible. The gizzard is muscular and internally provided with six cutical pointed teeth, for crushing the food.

The midgut is short and tubular lined with glandular endoderm. At the anterior end of midgut there are eight blind glandular

hepatic caeca (digestive/mesenteric caeca) which increase the surface area for absorption. The cells lining the mesenteron secrete enzymes. Most of the food nutrients are digested in the mesenteron and the end products of the digested food substances are absorbed by the cells of mesenteron and digestive caeca. The distal end of the midgut is indicated by the presence of malpighian tubules which are excretory in function (Figure 3.54).

The hindgut comprises of the ileum, colon, and rectum. The ileum is short and narrow and receives the openings of the malpighian tubules. On the other hand, colon is wider and longer than the rectum. The wall of the rectum is provided with six rectal papillae, which help in the absorption of water and salts. The digestive system terminates with the anal opening (anus) through which undigested material is removed in process known as egestion.

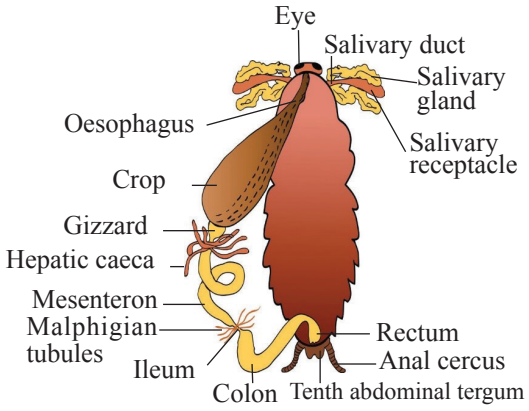


Figure 3.54 The digestive system of a female cockroach

Reproductive system of a male cockroach

The male cockroach has a pair of anal styles; the external structure which differentiate the male cockroach from female. Testes are small lobed masses (lobules) lying laterodorsally in the fourth and fifth abdominal segments. There are two testes (one on the right and the other on the left), each joined to a slender vas diferens (plural vasa diferentia) which connect to the wider ejaculatory duct.

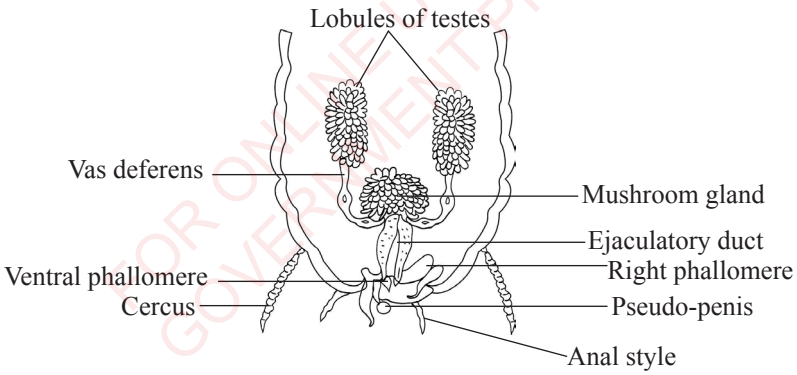


Figure 3.55 The reproductive system of a male cockroach

The testes produce sperms which transfered through the vasa differentia to the seminal vesicle. All sperms from a seminal vesicle are collected together into a large bundle called spermatophore (sperm pouch). There are three asymmetrical chitinous structures, called male gonapophyses or phallomeres; the right phallomere, the

left phallomere (largest) and the ventral phallomere (smallest). These, together with the pseudo-penis, form the organ used to transfer the sperm pouch to the female during copulation (Figure 3.55).

Reproductive system of a female cockroach

The female organs consist of ovaries, oviduct, vagina, genital chamber, spermathecae, collateral glands, and female gonapophyses (ovipositor processes). Ovaries of the cockroach are located laterally in the abdominal segments four, five and six. Each ovary consists of eight ovarioles. (Figure 3.56).

One oviduct from each side open into a genital chamber at a slit-like aperture. A pair of collateral glands also open in the genital chamber. A genital pouch or gynatrium is divisible into a genital chamber in front and the oothecal chamber behind.

Female gonapophyses consist of three pairs of chitinous rods hanging from the roof of the oothecal chamber into its cavity. They help in shaping the ootheca and depositing eggs in it. The ootheca of the cockroach contains sixteen fertilised eggs, coated with the secretions (protein, and dihydroxyphenol) of the colleterial glands. The eggs are lying in two rows, each with eight eggs. The female cockroach carries the ootheca for several days and finally protrude more and more until it is deposited to the dark crevice, and for about six weeks, the young cockroaches hatch out and grows into adult.

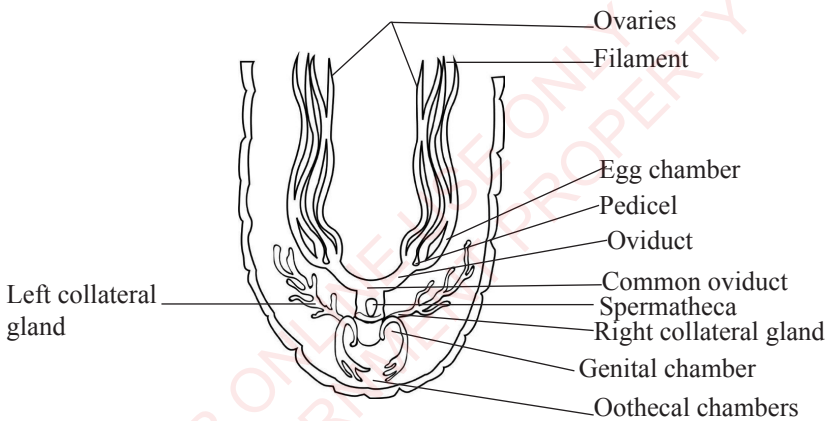


Figure 3.56 The reproductive system of a female cockroach

Dissection of a cockroach

Animals are dissected to analyse the structure and function of their body components. Dissection provides the crucial opportunity for students and other scientists to develop scientific observational skills. The methods of investigating gross structure depend on careful dissection or cutting apart, of an organism and on accurate descriptions of the body parts. Dissection involves attentive isolation and removal of individual organs, accessing the area in which the organs are situated, and systematically removing the anatomical connections of organ to its surrounding.

Dissection of a cockroach allows learning of the location and appearance of internal organs; distinguishing among different types of tissues within an insect body and to describe the major body systems. The following practical guidelines in dissecting a cockroach, permits the studies of internal features of the insect, including its heart, circulatory, digestive and reproductive systems. Materials necessary for the dissection of a cockroach include dissection kit, dissecting tray or board, a piece of thread, dissecting pins or office pins, scissors, fine-point forceps gloves and chloroform.

General procedure for dissecting a cockroach

a) Melt little wax in the centre of dissecting tray.

b) Wear a pair of gloves.

c) Cut the insect wings, antennae and legs close to their base.

d) Place the cockroach in the melted wax or use dissecting pins, to place the cockroach on its ventral side (sternum) while the dorsal side (tergum) is facing upwards.

e) Allow the wax to cool, and then the insect will be fixed (Figure 3.57).

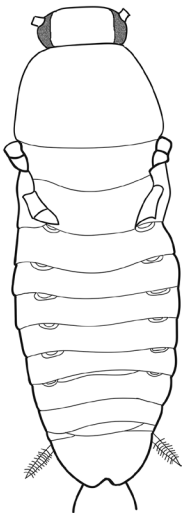
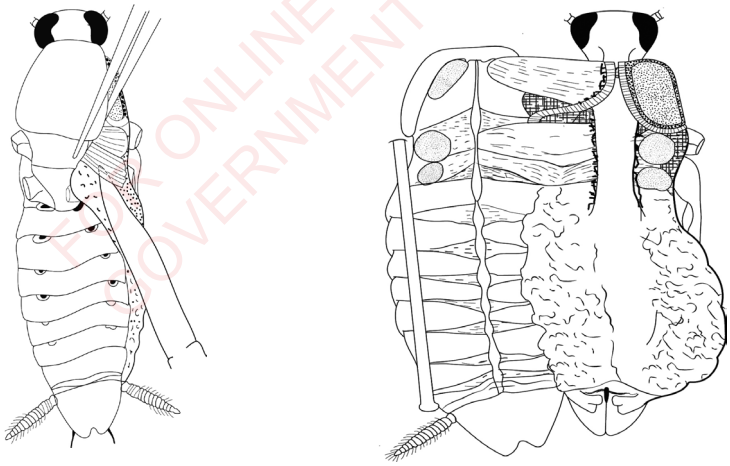


Figure 3.57 Cockroach fixed for dissection

f) Since cockroach's heart is on its dorsal side attached inside the terga and nervous system is on its ventral side, when dissecting, cut either on its left or right lateral side (pleural) from the last segment of the abdomen to the thorax.



(a) (b)

Figure 3.58 Fixed cockroach showing (a) lifted aside terga (b) pined terga

g) Carefully lift the last abdominal tergum using a forcep, then cut one side of the abdomen. Work forward by lifting aside the terga with forceps and cut around the edge with small scissor or scalpel up to the base of the head (Figure 3.58a).

h) Place a pin to hold the terga aside (you can use an optical pin to clearly pin it and ease observation of all parts in the terga as well as those of the abdominal cavity (Figure 3.58b).

i) Remove fats to expose the gut and other organs in the body cavity.

j) Cover your dissection with water to bring the organs float up, prevent them from drying up and to enable them being seen clearly.

k) Loosen the gut, deflect to one side and pin it to display all the systems (Figure 3.59).

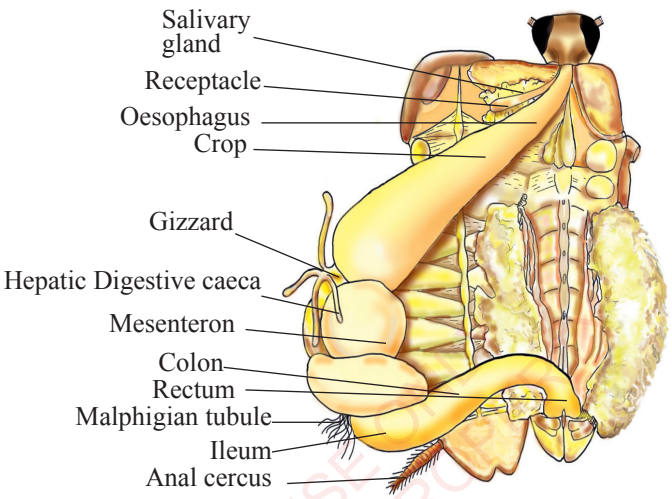


Figure 3.59 General view of the dissected cockroach

l) Make sure the body wall is neatly pinned aside, the dissection is generally neat with all required features; avoid damaging the organs and blocking the ducts.

m) Carefully examine all internal parts using a hand lens.

Safety precautions

1. Care should be taken when working with live specimens and apparatus, including dissection kit tools.
2. The working area, equipment and instruments used must be thoroughly cleaned and decontaminated after use, by using appropriate methods.
3. Good hygiene practices should be observed all the time; hands should be kept away from the mouth, nose, eyes, and face during and after dissection.

Hands should be thoroughly washed with soap or disinfectant immediately after conducting a dissection practical session.

4. All other safety laboratory rules should be observed; the teacher or laboratory technician should guide the students.

Activity 3.13 Dissection of a cockroach to display the digestive system

Materials

Fresh male or female cockroach, dissection kit, chloroform, dissecting tray or dish with wax intact, source of heat, and water.

Procedure

a) Collect a fresh male or female cockroach.

b) Prepare a dissecting tray or board and chloroform for anaesthetizing the specimen.

c) Dissect the cockroach in a usual way; deflect the gut to your right hand side, to fully display the digestive system.

Questions

1. Draw a diagram of your dissection and label only the parts of the digestive system. Compare your diagram with that of Figure 3.59.
2. State the function (s) of each labelled part.
3. Explain how the central location of a gizzard helps the organism in digestion.
4. Differentiate the crop from the digestive caeca.

Note:

1. The diagrams should be well drawn, large enough, generally neat and accurate.
2. The caption should be well indicated; when written on top of the diagram it should be capitalised and underlined, while when written below the diagram, the first later should be upper case and should not be underlined.
3. Label lines should be indicated in pencil; should be straight without arrows; and should not cross each other.
4. Labelling words should be on the required parts and written using blue or black ink.
5. The magnification of the diagram should correspond to the real specimen.

Activity 3:14 Dissection of a cockroach to display the reproductive system

Materials

Fresh male or female cockroach, dissection kit, chloroform, dissecting tray or board with wax intact, source of heat, and water.

Procedure

a) Collect a fresh male or female cockroach. With reasons identify the sex of your specimen.

b) Prepare a dissecting tray or dish and chloroform for anaesthetizing the specimen.

c) Dissect the cockroach in a usual way and deflect the gut to the left hand side of the animal, to fully display the reproductive system.

Questions

1. Draw a well labelled diagram of your dissection. Compare your diagram with that of Figure 3.55 or Figure 3.56.
2. State the role(s) of each labelled part.
3. Classify the organism to the class level.

Adaptations of Arthropods to their environment

Arthropods are the most abundant and diverse group of organisms on earth. They possess the following adaptive features, which help them to be a successful diverse group:

a) They possess a cuticle, which prevents water loss and makes them resistant to desiccation, predators, invasion by parasites, as well as physical and mechanical injury.

b) They have modified and specialised mouthparts according to their feeding habits; their mouthparts have mandibles for cutting and chewing, piercing, and sucking as in mosquitoes.

c) They have a well developed and efficient respiratory system extending towards the individual cells in which gaseous exchange takes place.

d) They possess flexible jointed appendages which facilitate rapid movement with minimum utilisation of muscles.

e) They possess sensory organs such as antennae, compound eyes, and cerci, which are capable of detecting slight movements, sounds, or chemicals.

f) They undergo moulting (ecdysis) process during development by removing their hard covers, and become soft to facilitate growth.

g) Their small and flattened body shapes enable them to hide into small cracks and crevices, where they live.

h) They possess coloured cuticle, which provides camouflage against predators.

i) Wings help them in dispersal and colonization of new habitats.

Economic importance of Arthropods

Arthropods play an important role in the world. However, not all arthropods are useful; some are harmful to other living organisms.

Advantages of Arthropods

a) Insects such as bees and butterflies are useful in agriculture; as they act as pollinators; many plants depend on insects for pollination.

b) They are used in industries for production of honey and wax materials; for example honey bees.

c) Insects are used in biological control of pests; in certain cases, insects have been very effective predators to reduce the number of pests. For example, lady beetles are used to kill aphids (the pest insects that transmit viruses to plants).

d) Many arthropods are used as food; they are a good source of protein for humans and other animals. Example include shrimps and lobsters, crabs, edible grasshoppers, locusts and grasshoppers, and many larvae of beetles and moths.

e) Insects are used in research and biological studies.

f) Insects such a as butterflies are valued for their beauty.

g) Many arthropods are used as indicators of the quality of environment.

Disadvantages of Arthropods

a) Some insects are vectors of animal and plant diseases. For example, mosquitoes carry *Plasmodium,* which cause malaria, and tsetse flies carry *Trypanosoma*, which cause sleeping sickness to human beings. Whiteflies carry Tomato yellow leaf curl virus which cause chlorosis in plants.

b) Some arthropods such as scorpions and centipedes bite human beings, release their poisons causing severe pains.

c) Some arthropods destroy crop plants; examples include locusts and the caterpillars of butterflies and moths.

d) Some arthropods are parasitic to mammals. Good examples of such arthropods are ticks, jiggers, and bedbugs, which grip themselves on human skin and suck blood.

3.7.5 Phylum Chordata

This is the third largest phylum in the kingdom Animalia. The phylum comprises of all animals that at some point during their lives, possess a hollow nerve cord and notochord.

General characteristics of phylum Chordata

a) They have a notochord at some stages of their development. Notochord is a stiff, flexible rod located dorsal to the gut and ventral to the nerve cord. In most chordates the notochord is replaced by a vertebral column (backbone) during adulthood.

b) They have visceral clefts which are slits perforating the body wall in the pharynx. They are useful in fishes and tadpole larva of amphibians for gaseous exchange as they use gills. In adult amphibians, reptiles, aves and mammals, the visceral clefts never develop gills.

c) They have endoskeletons made up of bone and cartilage.

d) They have post-anal tail.

e) They have a dorsal hollow nerve cord found above the notochord and below the epidermis. In higher chordates, the anterior part forms a brain and the posterior part forms a spinal cord.

f) They have ventrally positioned heart, which is a pumping organ as it pumps blood. Moreover, they have closed circulatory system.
g) They are triploblastic, coelomate animals with bilaterally symmetrical body.
h) They have two pairs of pentadactyl limbs or fins formed from more than one body segment. In higher chordates they are attached to the rest of the skeleton by pelvic and pectoral girdles.
i) Some members (cartilagenous fish, bony fish, amphibians and reptiles) are poikilothermic organisms, in that their body temperature depends on the environmental temperature changes while others (birds and mammals) are homeothermic organisms, as their body temperature remains constant regardless of the changes in external environmental temperature.

Classes of phylum Chordata

There are six classes of chordates namely; Chondrichthyes (cartilagenous fish such as shark and rays), Osteichthyes (bony fish such as tilapia and tuna), Amphibia (amphibians such as frog and toad), Reptilia (reptiles such as lizard, crocodile, and snake), Aves (birds such as hen, parrot, eagle, and pigeon) and Mammalia (mammals such as human, mouse, bat, rabbit and monkey).

Class Chondrichthyes

All members of this class have paired fins, paired nares, jaws, and a two chambered heart. Additionally, they have scales and endoskeletons made of cartilage. Members of class Chondrichthyes include dogfish, sharks, skates, and rays.

Distinctive features of class Chondrichthyes

Members of the class Chondrichthyes have the following unique features, which distinguish them from other fishes.
a) They possess placoid scales (tooth-like) covering their skin.
b) They have cartilaginous endoskeleton.
c) They have five pairs of visceral clefts as separate gill slits for gaseous exchange,with no opercula or gill covers.
d) They have ventral mouths.
e) They have heterocercal tail fins (asymmetric in shape), which prevent them from sinking as they lack swim bladder for buoyancy.
f) They have paired fleshy pectoral and pelvic fins for swimming.
g) They undergo internal fertilisation.

Structure of a shark

The body is more or less completely covered by placoid scales and has a lateral line that runs along the side of its body for detecting water currents and wave intensity. Its pectoral fin is anterior to the pelvic fins; usually the latter has claspers (pterygopodes) which are used as copulatory organs in males, and the caudal fin is heterocercal in shape. The mouth is located ventrally with teeth, which are constantly replaced. It has small eyes, which have lower lids used to cover the eyes during feeding (Figure 3.60). The gill slits are naked (no operculum) and has a spiracle which is a modified gill slit on top of the head that provides oxygenated blood directly to the eye and brain through a separate blood vessel. The intestine is short but with absorptive features increased by spiral valves.

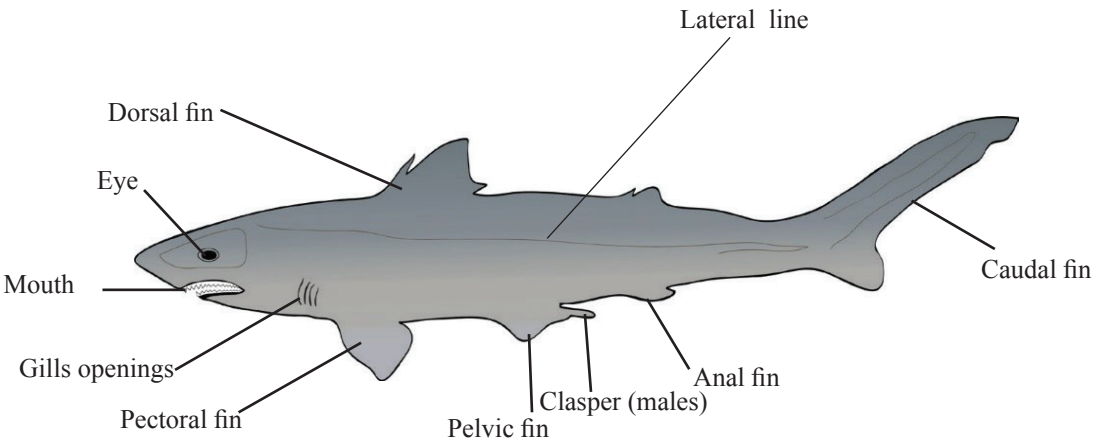


Figure 3.60 Structure of a shark

Class Osteichthyes

The class includes all bony fishes, such as tuna, tilapia, rainbow fish, herring and catfish. They are all aquatic organisms found in marine and fresh water bodies.

Distinctive features of class Osteichthyes

The following features differentiate members of the class Osteichthyes from other fishes.

a) They have thin, round, and cycloid scales (made up of bones) on their skins, which are impermeable to water, hence reducing water loss in marine environment, and restrict entry of water in fresh water fish.

b) They are bony fish, as they have bony skeletons.

c) They have paired pectoral and pelvic fins, supported by bony rays for swimming.

d) They have homocercal (symmetrical) tail fins.

e) They have four pairs of visceral clefts as separate gill openings covered by opercula.

f) They produce eggs and undergo external fertilisation.

g) They have swim bladder, which is in the abdominal cavity next to the backbone. This helps them to rise and sink (buoyancy) in water at particular depth without using much energy.

h) They have a terminal mouth.

Structure of Tilapia

The body is laterally flattened and tapered at both ends. Has a streamlined shape to overcome water resistance during swimming. Its body surface is covered by cycloid scales, which point backwards in order to reduce resistance during swimming. The fish has a lateral line that runs along the side of its body. The lateral line is a series of sensory organs called neuromasts that helps the fish to sense vibrations and water pressure for navigating and locating prey (Figure 3.61).

Figure 3.61 Structure of a tilapia

Class Amphibia

This class includes amphibians such as frogs, toads, caecilians as well as salamanders. Amphibians are tetrapod with the exception of caecilians, which are limbless. All amphibians lay eggs with the exception of some caecilians and some toads. For example members of the caecelian genera *Scolecomorphus* and *Schistometopum* give birth to live young. Also the toad genus *Nectophrynoides;* the members of this genus also give birth to live young. In the latter genus of *Nectophrvnoides* there is the Kihansi Spray Toad (*Nectophrynoides asperginis*); a small toad endemic to Tanzania with this unique characteristic of giving birth to live young toadlets.

The word amphibia refers to "double life", or life in water and on land. Amphibians are cold-blooded (ectothermic) vertebrates whose body temperature is not regulated by internal mechanisms. They inhabit a wide range of habitats, ranging from terrestrial to aquatic environments. Most amphibians spend a part of their life in aquatic environment and another part in terrestrial environment. Due to their life cycle and physiology, many amphibians are "tied" to water bodies in order to survive and reproduce. Normally, amphibians undergo metamorphosis from a juvenile as an aquatic larval form into a terrestrial adult.

Distinctive features of class Amphibia

Amphibians have the following distinctive features:

a) They dwell both in water and on land, as they depend on water for reproduction, hence the name amphibian, which means double life.

b) Amphibians' offspring begin their life cycle under water and breath by means of gills. As they grow to adulthood they move to terrestrial and breathe by means of either skin or lungs.

c) They have soft moist skin without scale, used for gaseous exchange to supplement lungs and buccal cavity.

d) Amphibian eggs have a jelly structure, which is prone to dehydration when exposed to air.

e) Amphibian's fertilization takes place outside the female body (with the exception of some caecilians and some toads including the Kihansi spray toad which give birth to live young).

f) They have two pairs of pentadactyl limbs for locomotion. The forelimbs have less musculature, while the hind limbs are webbed and long with powerful muscles for jumping.

g) They have long and protruding eyes for viewing preys widely and for avoiding enemies.

h) They have sticky tongue, which helps them in capturing prey.

i) They undergo metamorphosis for development from larval to adult stage in their life cycle.

Structure of a frog

The body of the adult frog is divisible into the head and trunk. The neck and tail parts are absent. The head is blunt, and the mouth is terminal, with two flexibly movable jaws. The head bears external nares, a pair of nostrils that lead into nasal passages. The eyes are large, bulged and covered by a nictitating membrane that protects them while in water. Behind the eye, there is a circular patch, a tympanum or eardrum, which receives sound signals.

The trunk widens in the middle, but tapers towards the end; four legs help in swimming and jumping. The hind limbs end in five digits and are larger and more muscular than the fore limbs that end in four digits. In both, fore and hind limbs, the digits are webbed for swimming purpose (Figure 3.62a). Frogs exhibit sexual dimorphism in that male frogs have sound producing vocal sacs and copulatory pads on the first digit of the fore limbs, whereas in female frogs these are absent. Moreover, the abdomen of the male frog is much slender than that of the female frog.

Structure of Kihansi spray toad

The Kihansi spray toad is a tiny toad of just about two centimetres in length, endemic to a two hectare area of Kihansi Gorge, of the Udzungwa Mountains, in the southern central of Tanzania. The toad is a highly specialized toad species, adapted to giving birth to a fully formed toadlet. Currently it is one of the very few amphibian species known to give birth to fully formed toadlets. The overall background colour of Kihansi spray toad is golden yellowish, with yellow and brown speckles on the dorsal surface, or dark lateral bands with adjacent lighter striping (Figure 3.62b). Ventrally, the skin is translucent, whitish near the throat and posterior, with the liver, fat bodies, and intestines visible through the ventral skin. Moreover, these toads have flaps over the nostrils that may be a special adaptation for living in the spray zone of waterfalls. On the feet, toes are partially webbed, with no external tympana.

Body systems of chordates

Chordates have a number of body systems which enable them to perform various physiological processes. Digestive and urinogenital systems of a frog or toad and rat or mouse will be emphasized in this text.

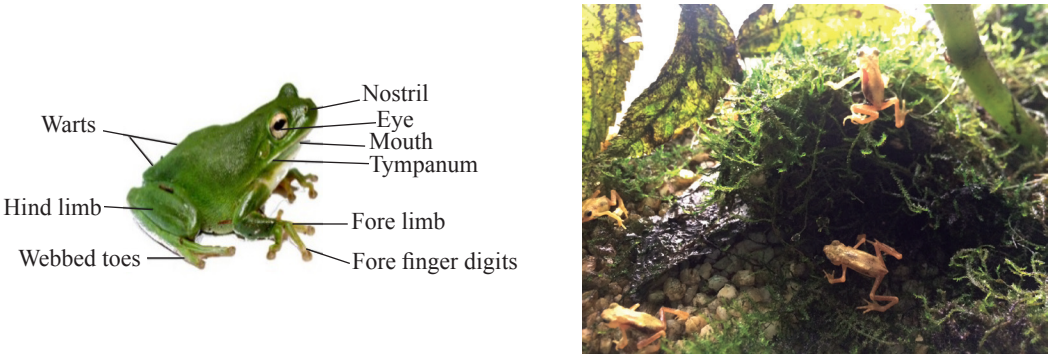


Figure 3.62 A photo showing the structure of (a) a frog (b) Kihansi spray toad

Source: UDSM, Zoology and Wildlife Conservation

Digestive system of a frog

The alimentary canal of a frog consists of the mouth, buccal cavity, pharynx, oesophagus, duodenum, ileum, and the rectum, which open into the cloaca at the anus. The mouth is wide for ingestion of large pieces of food material. They have flattened buccal cavity that emerges with the pharynx and it contains small, conical and sharp pointed teeth which are similar (homodont) used for cutting and crushing the food particles. Close to the angles of the jaws, there are two small openings, one on each side, known as eustachian tubes. These tubes are used for balancing pressure in the inner ear while the frog is swimming. Ventrally in the midline there is a narrow longitudinal slit (glottis) which leads into the larynx.

They have a short oesophagus that bears longitudinal folds, which close to prevent entry of air into the stomach and allow dilation during swallowing of food. Buccal cavity, pharynx and oesophagus have cilia, which constantly drive the mucus backward into the stomach to support swallowing and ensure that small food particles are not retained in the anterior parts. The stomach is thick walled, folded and elongated to increase the surface area for secretion of gastric juice used for digestion.

The duodenum lies parallel to the stomach and receives the secretions of bile and pancreas via hepato-pancreatic duct. The internal surface of the duodenum has many folds, which increase the surface area for secretion and absorption. The duodenum connects to the ileum, which has several coils, and longitudinal internal folds, where most of the digested food substances are absorbed here. The alimentary canal terminates in a rectum, which is short, and wide. Rectum is the place where feaces accumulate, and later pass periodically through the anal sphincter into the cloaca and eventually egested out of the body.

The liver consists of two large lobes (the left lobe and the median lobe). The median lobe is smaller than the left lobe. The gall bladder (lies between the liver lobes) and the bile duct run into the duodenum

through the pancreas. The pancreas lies between the stomach and the duodenum. The secretions are discharged into the bile duct, which become hepato-pancreatic duct and later discharge into the duodenum. In the mesentery near the duodenum lies a spherical red structure called spleen, which has no digestive role (Figure 3.63).

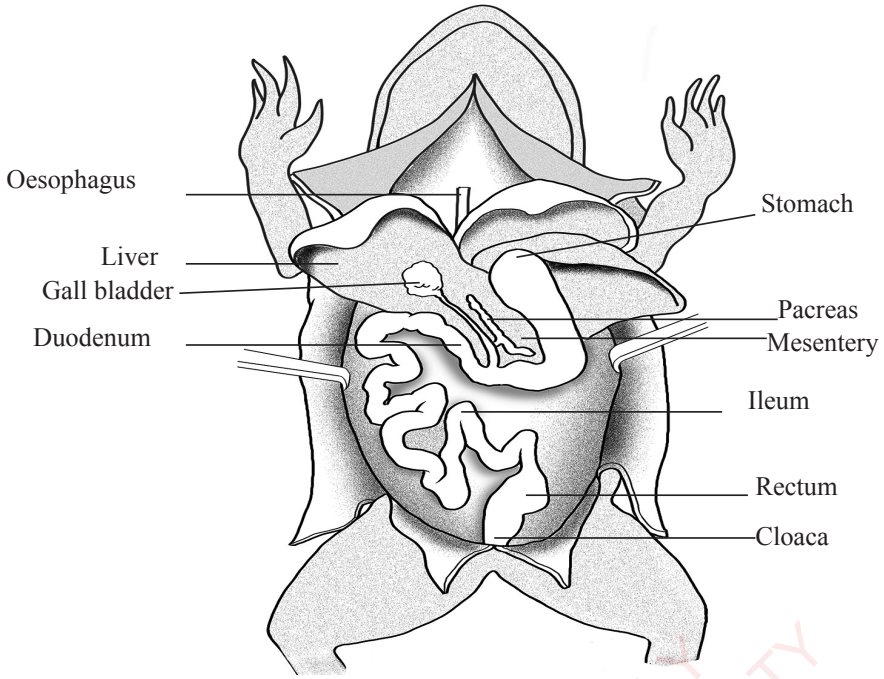


Figure 3.63 The digestive system of a frog

Urinogenital system of a male frog

A male frog is slender, with nuptial pads on the first finger which is one of the morphological features that distinguish it from female frog, which is fat, with an expanded abdomen due to the presence of eggs in the ovisacs. A male frog has two kidneys, which are dark red, oval, and somehow flattened, located near to the testes, ventrally and below the ureter. The ureter passes along the outer border of each kidney, and opens into the cloaca. The bladder is a thin sac arising as a ventral outgrowth, the cloaca, with its outlet closed by a sphincter. Since the ureter is not opening to the bladder, it is not a urinary bladder, but contains fluids possibly secreted by the blood vessels from its wall, which acts as a reserve of water during dry seasons. Cloaca is an outlet that serves as the only opening for digestive, reproductive and urinary tracts. Also, a frog has two testes, each suspended by a double fold of mesorchium. They lie ventrally below the front part of the kidneys, and from them there are several fine vasa efferentia that cross the mesorchium and enter the anterior kidney tubules which convey sperms to the ureter. In both left and right ureter, there is a pouch-like gland situated on each side of the male urinary bladder (vesicula seminalis) which store sperms until the breeding period (Figure 3.64).

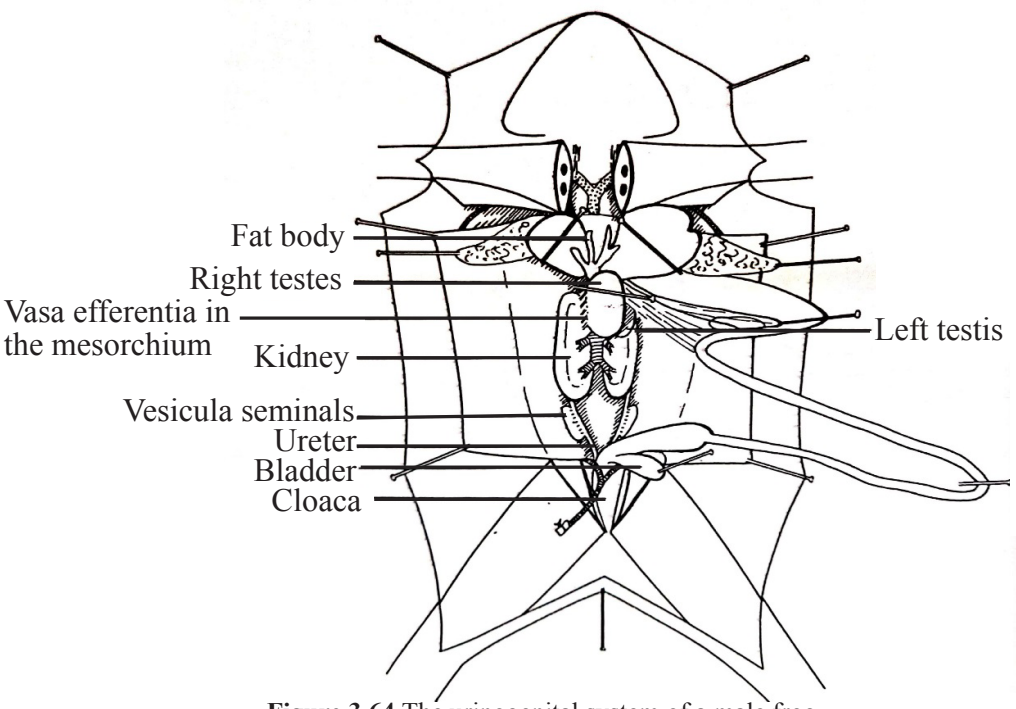


Figure 3.64 The urinogenital system of a male frog

Urinogenital system of a female frog

Female frog has left and right ovaries, lying in the same position as the testes, each suspended by a mesovarium and overlie the kidneys.

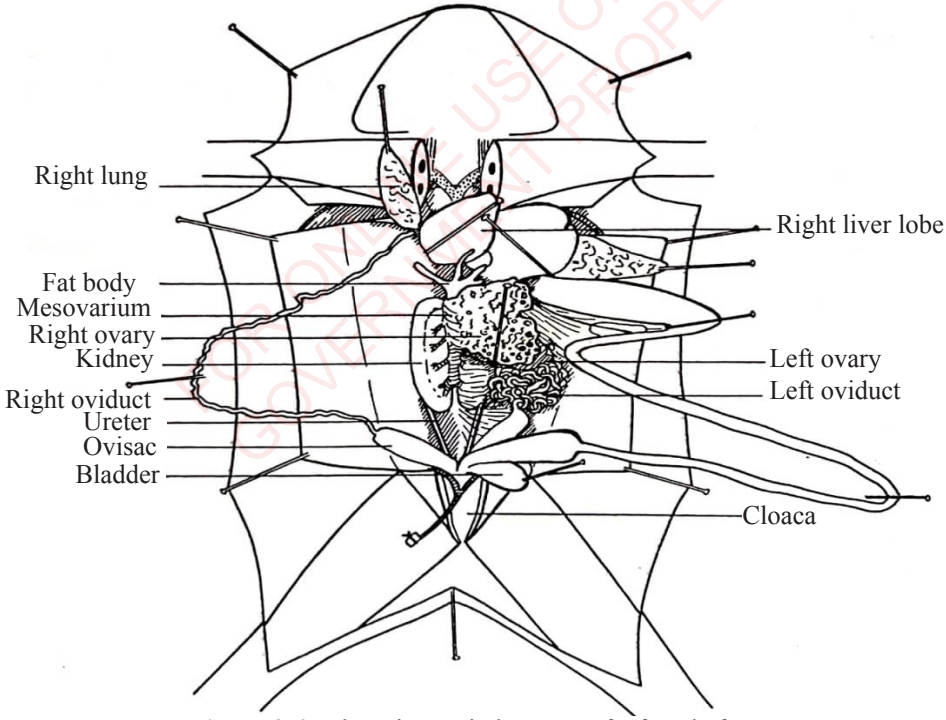


Figure 3.65 The urinogenital system of a female frog

The ovaries have flattened and numerous half black and half white eggs which can be seen through epithelium. They are connected to a long thin tube called oviduct. Each oviduct is dilated in its posterior region to form an ovisac, which store eggs until the laying period. The kidneys are connected to a tube called ureter that is used solely as a urinary duct, while in male frogs it passes both, sperms and urine. The ovisac and ureter open to the cloaca (Figure 3.65).

Dissection of a frog or toad

Dissecting a frog or toad is a common and important experience in the structural and anatomical studies of a typical vertebrate. The inside of a frog represents the general form for a vertebrate; as the organs present in a frog and the way they are laid out are similar enough to that of other animals.

General procedure for dissection of a frog or toad

a) Put on a pair of gloves.

b) Wet a piece of cotton wool with chloroform and put it inside an airtight container such as desiccator.

c) Put a live frog or toad inside the container, containing wet cotton wool, and leave it for about four to five minutes to anaesthetize it.

d) Take the frog or toad from the airtight container using forceps, place it on the dissecting tray or board and leave it for about 30 minutes to allow evaporation of chloroform.

e) Lay the frog or toad on its dorsal side (back), leaving the ventral side (abdomen) facing upwards (Figure 3.66).

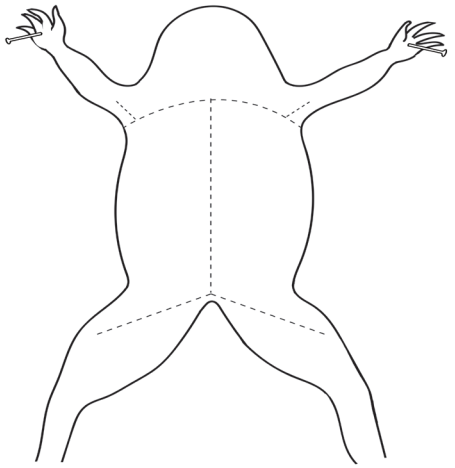


Figure 3.66 Positioning the frog or toad for dissection

f) Pin the frog down on the tray through the fore and hind limbs; the pin on each hand and foot should be at an angle to the tension put on it.

g) Use forceps to lift the skin of the abdomen and use scissors to make a slit in the mid ventral line, and then insert one blade of the scissors into the slit (Figure 3.67).

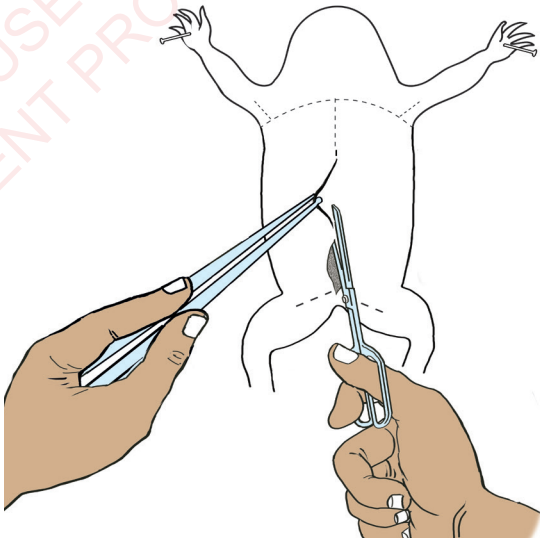


Figure 3.67 Opening the body cavity of an anesthetized frog or toad

Cut the skin forward to the level of the lower jaw; cut transversely at the level of each arm as far as the elbows. Similarly cut the skin back to the level of the pelvic girdle and cut towards the side of each hind limb down to the knee.

h) Hold the skin with forceps and loosen the skin from the underlying muscles using the surgical blade, turn the skin flap back and pin it.

i) Ligature the ventral abdominal vein at two sides. Use scissors to make two small slits and insert a loop of thread through the slits by using forceps and grip between their points; pull the thread through the slits and cut the loop, and then tie the threads apart in order to prevent bleeding and cut between the ligatured points (Figure 3.68).

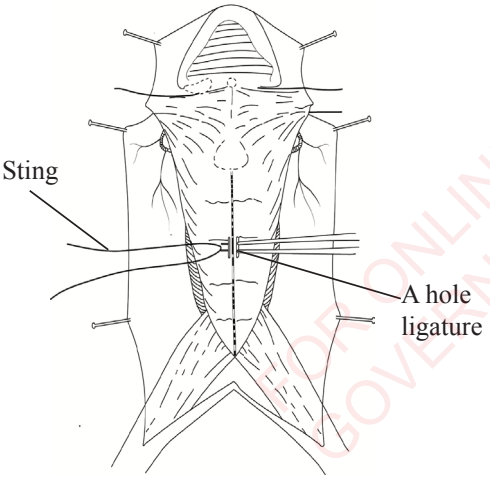


Figure 3.68 Ligaturing of the a frog

j) Lift the abdominal vein by using forceps and cut alongside it to the breast bone (xiphisternum). Then, hold the loose piece of the abdominal wall up and cut across the centre of the xiphisternum. Grip the cut piece, loosen it as far as the ligatured part and cut it close to that part; be careful not to cut the vein.

k) Cut through the pectoral girdle on either side of the mid-line and remove the central piece of the girdle to expose the heart, and then cut the body wall transversely below the arms.

l) Turn the tray in such a way that the legs are facing away from you, cut the body wall on either side of the mid-line to the pelvic area, remove the portion of the body wall and cut transversely to each leg. Pin aside the body wall and turn the tray to its original position. At this point the body cavity will be already opened up.

m) Remove any debris and leave the dissection clean.

n) Cover the dissection completely with water to avoid the drying of the organs and enhance clear observation.

o) With the help of a hand lens, observe the visceral (general) view of the dissected frog and note the position and shape of the organs (Figure 3.69).

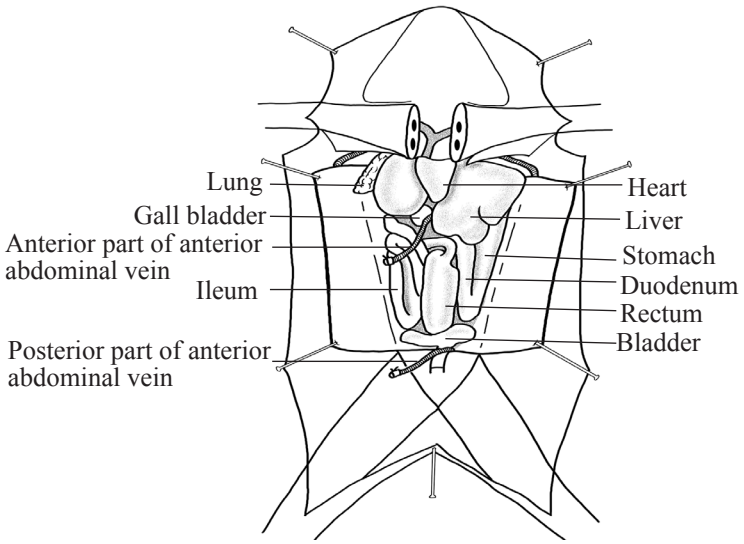


Figure 3.69 General view (visceral) of the dissected frog or toad

p) In displaying the digestive system, pin out the stomach to either side of the animal. Pin out the lungs, and turn the liver lobes forward and hold them in place with pins and grip the ileum to cut the mesentery and loosen the coils, but do not cut the mesentery of the duodenum and rectum. Rearrange the duodenum in position to expose the pancreas and pin out the ileum to your right hand side to make all features visible.

q) In displaying the urinogenital system, the cloaca should be opened by removing the ventral portion of the pelvic girdles. This should be done by inserting one blade of the scissors through the girdle, followed by cutting through the girdle as near to the mid line as possible, and lastly cutting on each side and removing the central portion of the girdle. Care should be taken to avoid cutting the blood vessels.

r) In case of a female frog; pin the right ovary on top of the left ovary, loosen and pin out the right oviduct and pin the bladder aside.

s) For the nervous system; remove the pins from the skin of the head and remove the floor of the mouth by cutting through angle of the jaw to expose the first spinal nerve (the hypoglossal nerve) which curves the pharynx and proceeds forward ventrally around the floor of the mouth to supply the tongue.

t) Remove the flesh from both fore limbs around the shoulders and remove the pins from the lungs and the stomach. Cut through the oesophagus and remove the lungs, heart, stomach and other parts of the alimentary canal.

u) Remove the reproductive and excretory parts, when removing the kidney. Take care not to cut the aorta.

v) Remove any remaining membranes surrounding the abdominal lymph sacs in order to expose the second spinal nerve called the brachial nerve (which

receives branches from the first and third nerve to form the brachial plexus) and other 3rd to 10th spinal nerves.

w) Trace the sympathetic cords on either side of the aorta, notice the sympathetic ganglia and identify the rami communicanes between the spinal nerves and the sympathetic ganglia.

x) Cut the flesh of the pelvic girdles through both thighs and trace the sciatic plexus (formed as an interconnection of the seventh, eighth, ninth and tenth) and the sciatic nerve (which passes down the leg close to the femur, and composed of the mainly joined eighth and ninth nerves).

Safety precautions

1. Care should be taken when working with live specimens such as frogs or toads, also chemicals like chloroform, as well as apparatus and equipment including the dissection kit tools.
2. The working area, equipment and instruments used must be thoroughly cleaned after use using appropriate methods. Good hygiene practices should be observed at all times; keep hands away from the mouth, nose, eyes and face during and after dissection; and wash hands thoroughly using an antiseptic or soap immediately after conducting a dissection practical session.
3. All other laboratory safety rules and regulations should be adhered to under the supervision of a teacher or laboratory technician whenever working in the laboratory.

Activity 3.15 Dissection of a frog/toad to display the visceral or general view (in situ) and digestive system.

Materials

Fresh male or female frog or toad, dissecting kit, dissecting tray or board, a piece of thread, chloroform, water, a pair of gloves, and cotton wool.

Procedure

a) Dissect the frog or toad in a usual way, open up the body cavity and pin aside the body wall to display the visceral (general) view of the animal in an undisturbed condition.

b) Deflect the alimentary canal to your right hand side; which is the left hand side of the animal and pin it to fully and display the digestive system.

Questions

1. Draw a large, neat well-labelled diagrams of the following:
   a) Visceral/general view.
   b) Digestive system.
   c) Compare your diagrams with that of Figures 3.63 and Figure 3.69.
2. Explain the significance of ligaturing and flooding the specimen with water.
3. State the role(s) of each part of the digestive system.
4. Classify the frog to class level.

Activity 3.16 Dissection of a frog to display the urinogenital system

Materials

Fresh male or female frog or toad, dissection kit, dissecting tray or dish, a piece of thread, chloroform, water, and cotton wool.

Procedure

a) Dissect the frog or toad in a usual way to open up the body cavity.
b) Deflect the alimentary canal to your right hand side and pin it to fully, display the urinogenital system.

Questions

1. With reasons, state the sex of your specimen.
2. Draw a large well-labelled diagram of your dissection. Compare your diagram with that of Figure 3.64 and Figure 3.65.
3. Outline the role (s) of each of the labelled parts.
4. How does the urethra of a male differ from that of a female?

Class Reptilia

The class comprises a group of animals including turtles, crocodiles, alligators, chameleons, tortoises, snakes, and lizards. Most of them have four limbs while others do not have limbs. Reptiles are found in diverse habitats, such as deserts, mountains, rocks, treetops and in water. They are mostly terrestrial with few aquatic members such as turtles and terrapins. They are cold-blooded (ectothermic) vertebrates. Their body temperature fluctuates according to the environmental temperature. Reptiles regulate their body temperature by behaviour, either by basking in the sun to warm themselves or by hiding under cover to cool their body. Most of them are tetrapods, with claws on their toes. Reptiles such as snakes and some lizards are legless, although they are descendants of four-limbed ancestors.

Distinctive features of class Reptilia

Reptiles possess the following unique features, which differentiate them from other chordates:

a) They have dry scaly skin with horny scales.
b) They have two pairs of pentadactyl limbs, except some members, such as snakes, which have no limbs.
c) They undergo internal fertilization and their fertilized yolky eggs are laid on land or retained until hatching.
d) They lay amniotic eggs that have a leathery shell to prevent rapid water loss.
e) Their eyes are located at the front of the head to facilitate binocular vision. Some reptiles can move each eye independently, and this helps them to find food and escape from predators.

Structure of a lizard

Lizards have dry scaly skin, and most of them have clawed feet and external ear openings. Most lizards are small, with four legs and a long tail that, in many species, is fragile and easily broken but regenerate later (Figure 3.70). The legs of some lizards are greatly shortened or vestigial, making animals such as the glass lizard or a slow worm have a snake-like appearance. They are distinguished from true snakes by their movable eyelids.

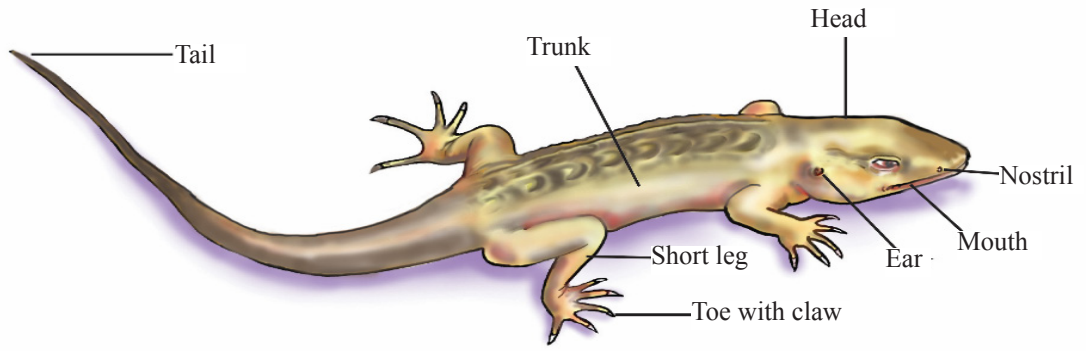


Figure 3.70 Structure of a lizard

Class Aves

The class Aves includes all birds. It is an extremely distinctive and successful class. Aves are bipedal feathered and warm-blooded (homoeothermous) animals, as they are able to maintain a constant body temperature. They have unique "one-way" breathing system. They have light, yet strong hollow bones, forming a skeleton in which many bones are fused or lost and have powerful flight muscles. Birds have evolved specific adaptations to enable them fly. They have fused hollow bones making birds have light weight, have a large keel for attaching flight muscles and have large chest muscles used for flight. Birds also have their fore limbs modified for flight and have feathers which are used for flying. They have also developed long flight feathers on the wings and tail to help birds attain balance and steer. Birds have developed air sacs connected to the lungs enabling them to extract more oxygen to release more energy to power flight. Also they have four chambered heart that enable them get more oxygen and avoid mixing oxygenated and deoxygenated blood. Birds have well developed brain enabling them to have quick reaction during flight. They have large eye to body ratio; and large eyes give birds good and keen eyesight important in flight. Birds can migrate during harsh conditions, since they have wings that enable them to move fast. Birds are widely spread all over the world; some are found in very cold snowy environments and others in dry and hot environments.

Structure of a pigeon

The body is spindle shaped and the size varies from 20-25 cm. The body is divided into the head, neck, trunk, and tail. Most parts of the body are covered by feathers. The head is small and rounded (Figure 3.71). It is anteriorly pointed into a short beak. On the lateral side of the head, there is a pair of prominent eyes. The ear comprises of small apertures on the posterior side of the eyes. Each aperture remains covered by a special group of feathers called auricular feathers. Each aperture leads to a canal called external auditory meatus, which is closed below by the tympanic membrane. The trunk is the greatest and widest part of the body. It is boat-shaped and bears a pair of wings and a pair of legs. The entire foot is covered with horny epidermal scales. At the hind end of the trunk is the cloaca aperture.

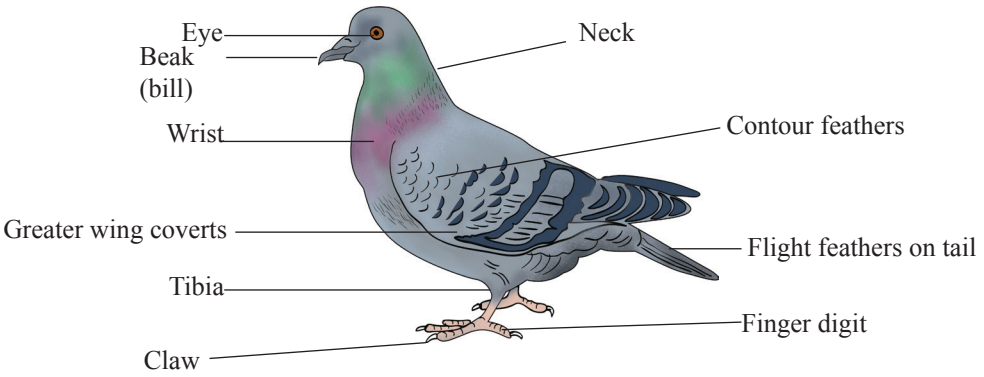


Figure 3.71 Structure of a pigeon

Distinctive features of the class Aves

Aves are different from other chordates due to possession of the following features:

a) Their bodies are covered by overlapping feathers.

b) They lost teeth; instead, they have modified mouthparts into different types of beaks (bills). Beaks are adapted for many different feeding habits, such as seed crushing, fruit scooping, flesh tearing, nectar sipping, and wood chiseling.

c) They have cylindrical, long necks connecting heads and trunks.

d) They have two pairs of pentadactyl limbs. The front limbs are modified into a pair of wings, which bear quill feathers for flight, while the hind limbs are covered by scales and are adapted for perching, walking or swimming.

e) They undergo internal fertilisation and produce eggs with calcareous shells.

f) Their sternum forms a sharp ventral keel, providing muscles attachment for flight.

g) They have oil gland above the cloaca, which preens the feather so that they become waterproof. Ostrich and parrot lack oil gland.

h) Their alimentary canal has additional chambers called crop and gizzard. The crop stores and softens the food, while the gizzard helps in crushing and churning the food.

i) Birds are capable of flying except for a few species such as ostrich, penguins, and kiwi.

Class Mammalia

The class Mammalia consists of all animals with mammary glands. It is an extremely diverse and very advanced group in the kingdom Animalia. Members of the class Mammalia include: human, mouse, rabbit, cow, lion, bat, whale, and donkey.

Distinctive features of class mammalia

Mammals are different from other chordates because:

a) They have fur or hair that cover their skin. The skin is glandular, with two types of glands, namely, sebaceous and sweat glands.

b) Females (mothers) have mammary glands, which produce milk for their newborn.

c) They have external ears called pinna in addition to middle and inner ears, which are used for collection of sound waves and leading them to ear canal. The middle ear has three small soft bones called ear ossicles namely; malleus, incus, and stapes.

d) They have heterotrophic mode of nutrition with different types of teeth (heterodont dentition) for different functions, depending on the mode of feeding.

e) They have highly developed brains.

f) They have muscular diaphragm, which separates the thorax from abdominal cavity.

g) They are viviparous (give birth to young ones). The developing foetus is held in the uterus, and gets nourishment through placenta, except in primitive animals like kangaroo, which bear immature young ones and duck-billed platypus, and echidna which lay eggs.

Structure of a mouse

Structurally, an adult mouse has an average length of 7.5-10 cm. Its body is divided into head, neck, and trunk. The head bears external ear flaps called pinnae, eyes, nostrils and a mouth. The latter has long, hair extensions called vibrissae or tactile whiskers (Figure 3.72). The neck is short and wide, connecting the head to the trunk. The trunk bears four walking legs, two short hind legs and two long front legs, each with five digits. The trunk also bears a long tail which is either hairless or has sparse covering of hair. The whole body of the mammal is covered by fur (pelage).

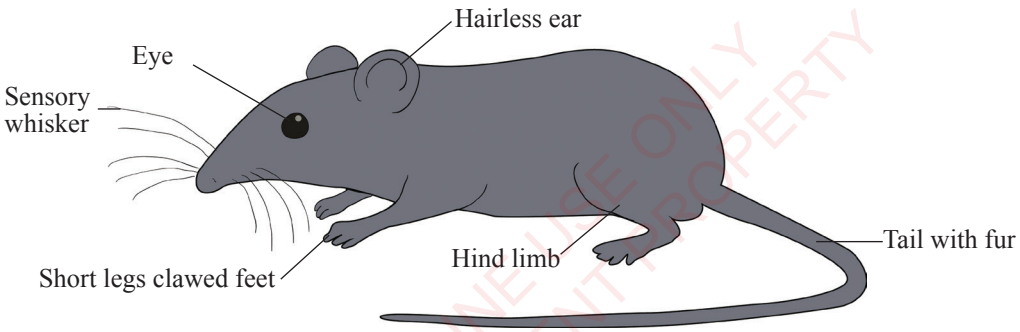


Figure 3.72 Structure of a mouse

Digestive system of a mouse

The alimentary canal of a mouse starts from the mouth to the anus. The mouth consists of sixteen teeth; twelve molar and four incisors (two on the upper jaw and the other two on the lower jaw). The lower incisors teeth are more developed, pointed, sharp and longer than the rest, and are used for cutting the food into small chewable pieces. Down from the mouth, there are oesophagus, stomach, pancreas, and small intestine. The small intestine has three segments (duodenum, jejunum and ileum), followed by the large intestine, with four segments namely: caecum, colon, rectum and anus. The stomach is a hollow organ (pouch-shaped) lying in the ventral part of the abdomen, and is partly covered by liver

lobes. It is concerned with the digestion of food and temporary storage before further digestion in the small intestine (Figure 3.73).

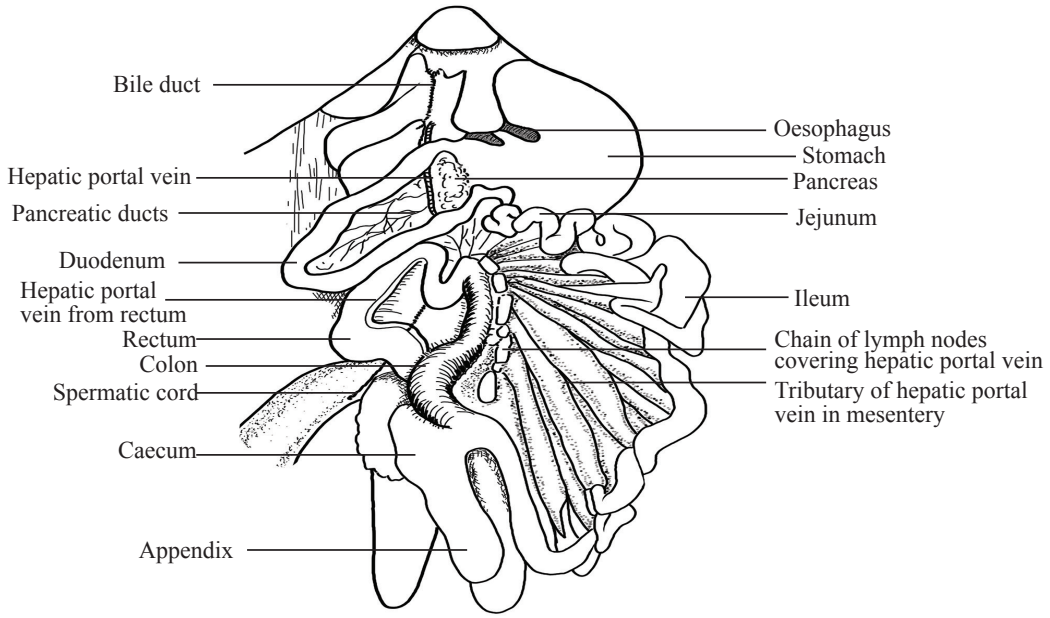


Figure 3.73 The digestive system of a mouse

The liver has four lobes; one on the left, two on the right, and one in the centre. The liver has two functions in digestion: secretion of bile and receiving the absorbed food from the small intestine through hepatic portal vein. It lacks gall-bladder, instead the cystic ducts from the liver lobes join to form the bile duct which conveys bile to the duodenum. The hepatic portal vein runs from the liver to the intestines; covered by a chain of lymph nodes and form branches in the mesentery (plural mesenteries) and other parts of the intestine.

The mesenteries are the continuous set of support tissues, which attach the intestines to the posterior wall of the abdomen. They support efficient digestion and maximum absorption of digested food by helping in storage of fat and allowing lymphatics, blood vessels, and nerves to supply the intestines. The pancreas secretes digestive enzymes, which pass through the numerous small pancreatic ducts that enter the duodenum for digestion. The main functions of the small intestine are digestion and absorption of the products of digestion. Duodenum is the first part of the small intestine, connected to the stomach by a pyloric sphincter; which receives and digests the released food from the stomach using bile and other digestive juices. Jejunum and ileum are similar in both structure and function. They are both involved in digestion of food as well as absorption of nutrients. The overall functions of the large intestine is to complete absorption of water mainly from undigested food particles, manufacture of certain vitamins, formation of feaces and expelling faeces from the body through the anus. The main role of caecum is the absorption of water and salts remained after completion of digestion in the small intestine, as well as mixing and lubricating

its contents using the mucus secreted from its internal thick wall of mucous membrane. Rectum connects the colon to the anus, which aids in temporary storage of feaces before its release (when the sphincter contracts), and aids their release through the anus (when the sphincter relaxes).

Urinogenital system of a male mouse

The urinary and reproductive systems are integrated in some ways and are usually studied together as urinogenital system. However, the excretory system eliminates waste product and the reproductive system produces sperms in male and eggs in female and provide conducive environment for fertilization and their developing foetus or embryo.

The kidneys are bean shaped structures found on the back of the abdominal cavity on either side of the spine and are embedded in the fats. On top of each kidney are small glands called adrenal glands (Figure 3.74). In addition, a small and delicate tube called ureter is attached to each kidney, which leads the urine to the urinary bladder. The urinary bladder is connected to the urethra, which carries urine from the bladder to the urethral orifice then to the outside through the penis.

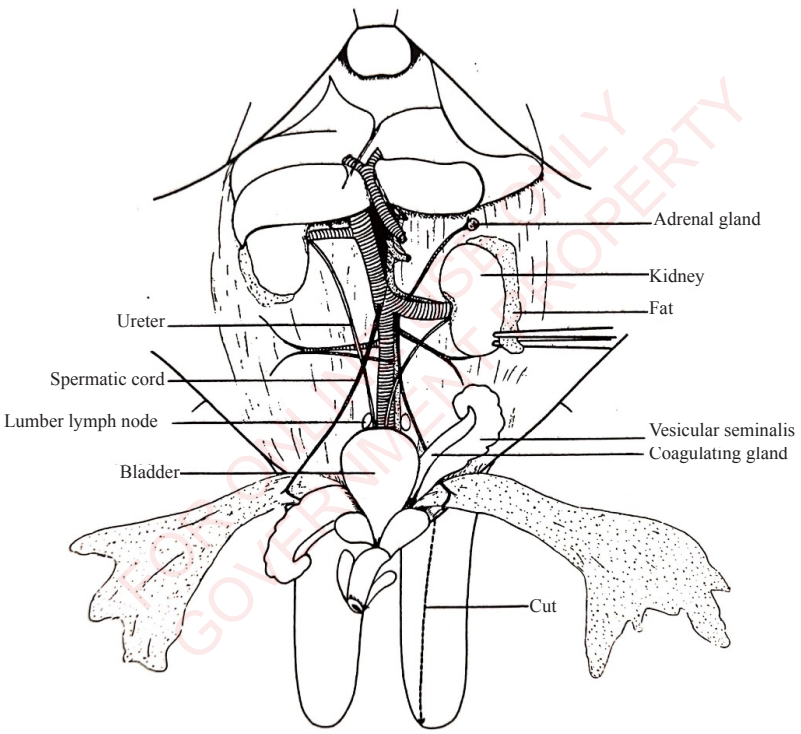


Figure 3.74 The urinogenital system of a male mouse

Males have two openings on the pelvic area; genital opening and the anus. The genital opening passes both urine and sperms via a penis hanging out from or between the two

scrotal sacs. The scrotal sacs protect the testes (singular testis). The testes (which secrete sperms) are connected to a coiled tube called epididymis which collects the produced sperms and store them. The epididymis is very long twice the length of the testis. It has caput, corpus, and caudal regions and it is connected to the tubular vas deferens which transports sperms from the epididymis to the urethra. The urethra not only carries the urine, but also sperms through the penis to the outside of the body. On the left and right of the urinary bladder there are folded glands called the seminal vesicles (vesicula seminalis) bearing a coagulating gland, and below the urinary bladder, which store urine. There are other glands known as prostate glands at each side of the urethra and Cowper's glands, which are small ovoid structures, found at the root of the penis. There are two preputial glands, each wrapped on one side of the ventral wall.

Urinogenital system of a female mouse

The female pelvic area has three openings; urethral opening, genital (vaginal) opening and the anus. The kidney and ureter have the same composition as in males, except that the urethra, which passes both urine and sperms in males, in females the urethra passes only urine conveyed from the bladder and passes to the outside environment through urethral opening. The vagina terminates to the long duplex tubes one on each side called uterus, which later accommodates multiple developing foetus. At the tip of each uterus is an ovary (eggs producing gland) which is enclosed within a thin-walled ovarian sac surrounded by fats. Each ovary is connected to the uterus via a single small undulating coils called fallopian tube (Figure 3.75).

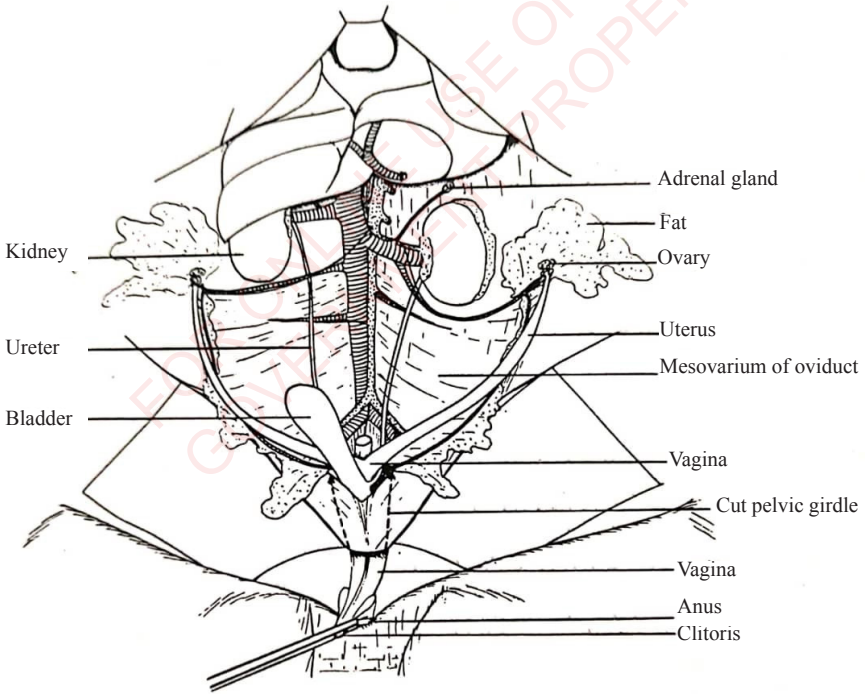


Figure 3.75 The urinogenital system of a female mouse

Dissection of mouse or rat

A mouse or rat is a typical vertebrate animal whose many aspects of structural organisation are similar to those of other mammals, including human being. Moreover, mice or rats are also important research tool for modeling human disease progression and development in the laboratory. They have also helped to speed up the progress of research and enabled the development of important new drugs. Therefore, by examining the physiology, anatomy and metabolism of a mouse or rat, scientists can gain a valuable insight into how human system functions. Despite the differences in their body size and appearance, Mice/rats share a distinct genetic similarity to humans; and their ability to reproduce and mature quickly make them efficient and economical candidate mammals for scientific studies.

The purpose of conducting rat or mouse dissection is to explore and study the internal organs and systems of the basic mammalian anatomy.

General procedure of dissection of a mouse or rat

a) Put on a pair of gloves.

b) Place a live male or female mouse or rat in a container with a lid and anaesthetize it using chloroform soaked in a small roll of cotton wool for five minutes.

c) Lay the mouse or rat on the dissecting tray or dish, with the ventral side (abdomen) facing upwards (Figure 3.76). Pin it down on the tray through the fore and hind limbs, make sure that the pins face outwards.

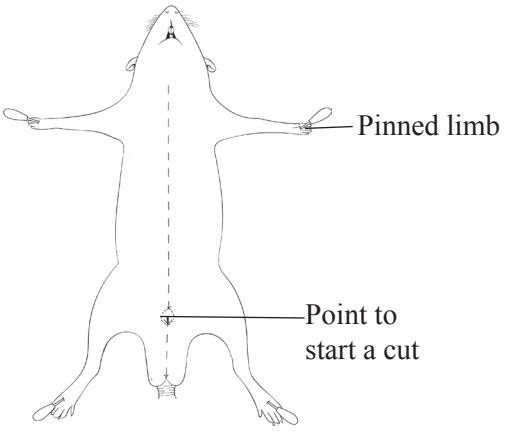


Figure 3.76 Positioning the mouse or rat for dissection

d) Lift the skin in the mid-ventral line using forceps, and cut to make a small slit (Figure 3.77). Cut forward to the level of the lower lip and backwards around the penis and between the scrotal for a male specimen while for the female cut the skin backward as far as the anus, passing either side of urinary and genital apertures.

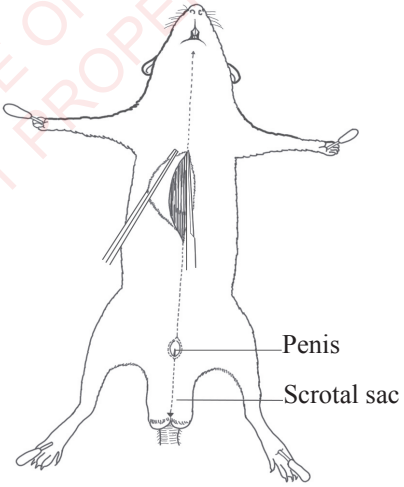


Figure 3.77 Opening the body cavity of an anesthetized mouse or rat

e) Use fingers to pull the skin aside, loosen it from the body wall, stretch it and pin it back.

f) Lift the abdominal wall using forceps, make an incision and cut up to the xiphoid cartilage and down to the left and right ribs. Stretch the body wall and pin it aside (Figure 3.78). Examine the contents of the abdominal cavity in undisturbed condition (in situ or visceral/general view) and draw a well labelled diagram.

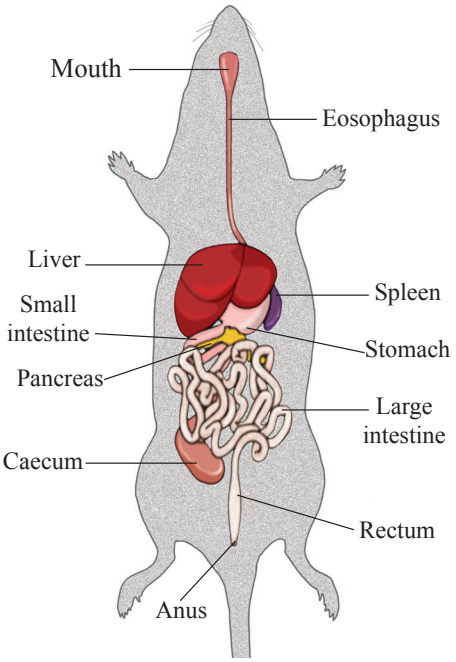


Figure 3.78 General view of the dissected mouse or rat

g) To display the digestive system, adjust the positions of the alimentary canal by moving the bulk of the intestine to the left hand side of the specimen to expose the duodenum and the colon.

h) Grip the duodenum and colon, pull them apart to expose hepatic portal vein and turn the bulk of the intestines over to untwist them, rearrange the digestive structures and draw a well labelled diagram.

i) When displaying urinogenital system, the alimentary canal should be removed first followed by the removal of fats from the kidneys using blunt forceps and clear the ureter.

j) In male mouse, open the scrotal sac by cutting its ventral wall to expose the testes, caudal and caput epididymis as well as the vas deferens. Lay the bladder, seminal vesicles, coagulating glands and prostate glands on one side.

k) In female mouse/rat grip the clitoris, pull it gently so that the urethra is held away from the pelvis, and cut the ventral part of the girdle. Lift the oviducts and remove the mesovarium to expose ureters on both sides, remove the fat bodies from the kidneys and ureter, but leave them around the ovaries (the ovaries are enclosed within the thin walled ovarian sac and connected to a very small and much coiled fallopian tube) and observe the very long tube called fallopian tube near to the uterus.

Safety precautions

1. Consider issues such as allergies or sneezing from loose rat or mouse furs.
2. Rat or mouse may bite a person and cause pains, so be careful when dealing with live a rat or mouse.
3. Good hygiene practices should be observed all the time; keep hands away from the mouth, nose, and eyes and face during and after dissection and wash hands with antiseptic soap immediately after a dissection practical session.

4. Other safety laboratory rules and precautions should be adhered to under the supervision of a teacher or laboratory technician.

Activity 3.17 Dissection of a rat or mouse to display the digestive and urinogenital systems

Materials

Fresh male or female rat or mouse, dissection kit, dissecting tray or dish, chloroform, and cotton wool.

Procedure

a) Collect a live male or female rat or mouse; put it in a container with lid and anaesthetize it with chloroform soaked in a small roll of cotton wool for about five minutes.

b) Dissect a mouse in the usual way, to fully display the digestive system and urinogenital system.

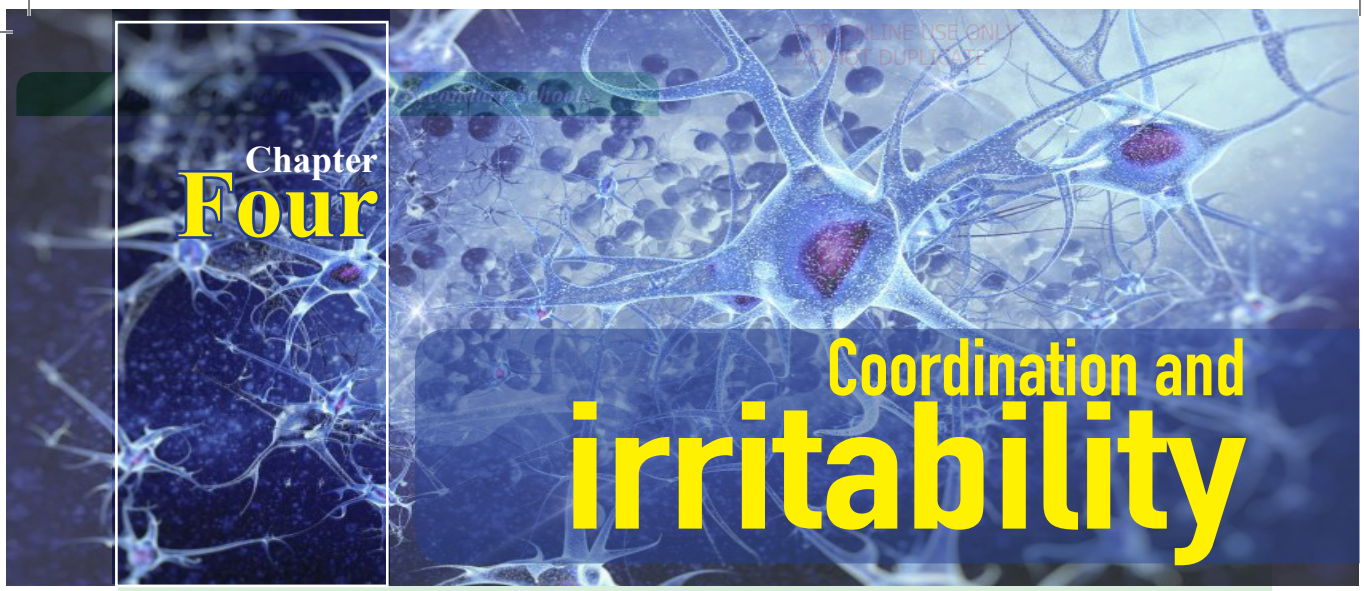
Questions

1. Draw well labelled diagrams of the displayed systems in (b) above. Compare your diagrams with those of Figures 3.73, 3.74 and 3.75 respectively.
2. Explain the role(s) of each labelled part.
3. How does the urethra of a female rat or mouse differ from that of a male?
4. Classify the organism to class level.

Revision questions

1. With example(s) categorize viruses based on the nature of their genomes and morphology of their capsids.
2. What are the advantages and disadvantages of viruses?
3. Classify bacteria on the basis of the following:
   a) Morphology
   b) Gram stain test
4. Account for the advantages and disadvantages of members of kingdom Monera.
5. Explain the adaptations of *Entamoeba histolytica* to its mode of life.
6. Explain how *Plasmodium* is able to exist in humans and mosquitoes.
7. Describe the general and distinctive features of phylum Apicomplexa.
8. *Euglena* is an ancestor of plants and animals. Explain.
9. How is *Phytophthora* adapted to its mode of life?
10. *Spirogyra* resembles plants. Explain.
11. Explain with examples the advantages and disadvantages of Protoctists.
12. Describe the general and distinctive features of basidiomycetes.
13. Explain the advantages and disadvantages of fungi.
14. Differentiate between coniferophytes and angiospermophytes.

15. Explain the economic importance of kingdom Plantae.
16. Arthropods are the most successful animals on the earth. Justify.
17. How are Aves adapted for flight?
18. Classify the following organisms to their class level; moss plant, monkey, cactus, blood fluke, snake, mite, housefly, sugarcane, earthworm, Kihansi spray toad, shark, and bean plant.
19. Explain the distinctive features of amphibians.
20. How are the following organisms adapted to their mode of life?
    a) Fern plant
    b) Earthworm
    c) Kihansi spray toad.
21. Explain the adaptive features of mammals.



Chapter
Four
Coordination and irritability

Introduction

In organisms the body parts work together for various roles, resulting into a coordinated body. Animals have two systems of coordination namely nervous coordination and endocrine coordination, while plants have hormonal coordination. Nervous coordination is accomplished by the nervous system composed of nerve fibres, brain and spinal cord, whereas hormonal coordination is accomplished by endocrine system which is composed of the endocrine glands. In plants, responses are in the form of slow modified growth or movements called turgor movement. In this chapter you will learn about nervous coordination in mammals, hormonal coordination in mammals, coordination in plants, and phytohormones (plant hormone).

4.1 Nervous coordination in mammals

As in other animals, nervous coordination in mammals is accomplished by the nervous system. The mammalian nervous system consists of a central nervous system and peripheral nervous system. The central nervous system is made up of the brain and spinal cord, whereas the peripheral nervous system is made up of the nerve fibres. The nerve fibres branch from the central nervous system and extend to all parts of the body. Coordination is accomplished through a set of signals channeled into a series of nerve cells. The nerves that transmit signals from the body to the central nervous system are called afferent nerves, and they include sensory and relay neurones, while those nerves which transmit signals from the brain are called motor or efferent nerves. Nervous coordination enables a mammal to respond rapidly to external and internal stimuli.

Nervous tissue

The nervous tissue is a specialized tissue made up of nerve cells (neurones). A neurone is the basic unit structure of the nervous tissue which consists of the cell body, dendrites and axon. Nervous tissues make up the Central Nervous System (CNS) and Peripheral Nervous System (PNS). The central nervous system consists of the brain and spinal

cord, while the peripheral nervous system comprises of the cranial and spinal nerves, which are packed together with their motor and sensory endings. Nervous tissue is the main tissue component of the nervous system and it consists of closely packed nerve cells or neurones with very small intercellular spaces. Nervous tissue contains two types of cells, namely; neurones and neuroglia. Neurones are specialized nerve cells which generate and conduct nerve impulses. Neuroglia are non-neuronal cells which assist in propagation of the nerve impulses and provision of nutrients to the neurones. Neuroglia also serve as supporting cells that provide electrical insulation and remove debris. Cells of the neuroglia produce myelin sheath that increases the speed of impulses along the axon of the neuronal fibres and offers protection for the axon.

Types of neuroglia

There are six types of neuroglia, four of which are found in the CNS and two in the PNS. The neuroglia found in the CNS include astrocytes, microglial cells, ependymal cells and oligodendrocytes, while those found in PNS include satellite cells and Schwann cells (Figure 4.1 a to f). The collection of glia cells residing within the walls of intestinal tract, beginning in the oesophagus and extending down to the anus are known as enteric glia. The six types of neuroglia are explained below:

a) Microglial cell

These are the smallest neuroglial cells (Figure 4.1a). They are macrophage cells that make up the primary immune system for the CNS. These phagocytic cells help to remove bacteria and waste (cleaning neuronal debris).

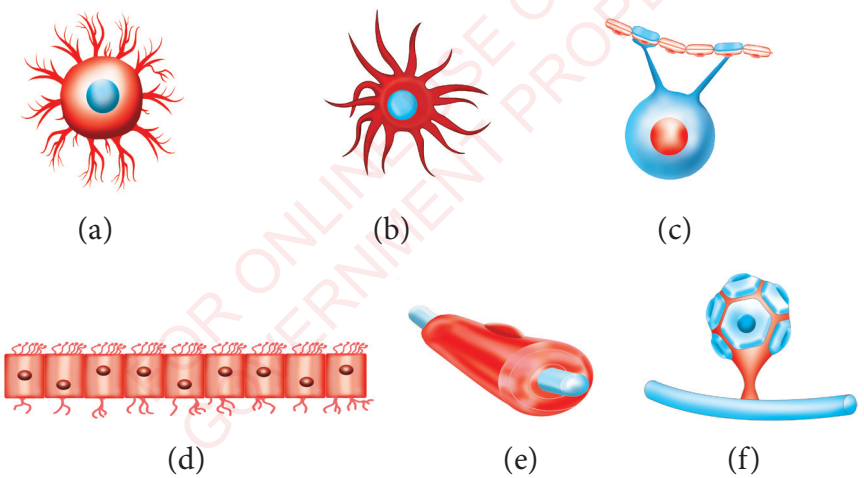


Figure 4.1 Types of neuroglia (a) microglial (b) astrocytes (c) oligodendrocytes (d) ependymal (e) schwann and (f) satellite cells

b) Astrocytes

These are star-shaped macroglial cells with many processes (Figure 4.1b). They are the most abundant glial cells in the CNS. Their roles are to provide metabolic and structural support to the neurones.

c) Oligodendrocytes

These are cells with very few processes (Figure 4.1c). They are found in the CNS. They form myelin sheath on the axons of a neurone which have lipid-based insulation for increasing the speed at which the action potential can travel down the axons.

d) Ependymal cells

These are ciliated cells which line up the central cavities of the brain and spinal cord where they form a fairly permeable barrier between cerebrospinal fluid that fills these cavities (Figure 4.1d).

e) Schwann cells

These are equivalent to oligodendrocytes (Figure 4.1e). They surround nerve fibres in the PNS. They help to maintain axons and form myelin sheaths in the PNS.

f) Satellite cells

They line the surface of neuronal cell bodies in ganglia within the PNS (Figure 4.1f). They are analogous to astrocytes.

Adaptive features of nervous tissues

The nervous tissues have the following adaptive features:

a) They have nerve cells (neurones) that receive information from sensory parts and send or transmit it to the CNS for interpretation and then to the effector for a response. An effector is any part of the body that produces response. Examples of effectors include a muscle and a gland.

b) The cells of the nervous tissues are tightly packed for effective working of the tissue.

c) The cells of the nervous tissues have large number (high concentration) of mitochondria which help to generate energy. This is important because nervous tissues require large amount of energy for efficient functioning.

d) They have neuroglia (glial cells) that provide protection and support to the tissues.

e) The cells in the PNS are capable of regenerating themselves. This is due to the presence of neurolemma (also known as neurilemma).

f) The cells in the nervous tissues produce neurotransmitter chemicals which act as conveyors that carry impulses from one neurone to another across the synaptic gap.

g) Nerve cells or neurones have nodes of Ranvier and fatty myelin sheath which facilitate rapid transmission of impulses.

The Central Nervous System (CNS)

The CNS, which consists of the brain and the spinal cord has the grey matter and white matter. The grey matter is comprised of cell bodies, dendrites, unmyelinated axons, and very few myelinated axons. In contrast, the white matter is comprised of myelinated axons. The main function of the central nervous system is to integrate information from various sources. The collection, both from internal and external environment is done by receptors. They

usually form the sensory system along with neurones which transmit the collected information from different parts. The collected information is processed and integrated in the central nervous system, and finally the information is transmitted to effectors (muscles and glands) which produce appropriate responses.

Functions of the nervous system

The nervous system has the following functions:

a) It receives stimuli from the environment using receptor cells or sensory input.

b) It converts the stimuli into electrical impulses by the process called transduction.

c) It transmits nerve impulses. The impulse is transmitted from the sensory receptor to the CNS and then to the effector, which is capable of producing an appropriate response.

d) It stores information so that behaviour can be modified according to the past stimuli.

Neurones

Nerve cells or neurones are conducting cells of the nervous system found between the receptors and effectors. These spread throughout the body of an organism and form a communication network. Neurones are the basic structural and functional units of the nervous system. They are responsible for transmission of impulses from one part of the body to another.

The main portion of the neurone is the cell body, which contains a nucleus. The cytoplasm of the cell bodies contains granules called Nissl's bodies. Extending from the cell body are one or more short extensions called dendrites. These receive signals from the sensory receptors and transmit electrical signals or impulses to the cell body. The neurone also contains long extension called axon. In some cells, axons are covered by a fatty layer of material known as myelin sheath. Within the cell body there are fine neurofibrils that extend from the dendrites to the axon. An axon is a long, stem-like part of the cell that sends action potential signals to the next cell. Outside the myelin sheath is a cellular layer called neurilemma, containings sheath of Schwan cells which are essential for rapid propagation of nerve impulse as well as nourishment and insulation of the axon. The myelin sheath together with neurilemma constitute the medullary sheath (Figure 4.2), inside the axon there is a space containing charged ions called axoplasm.

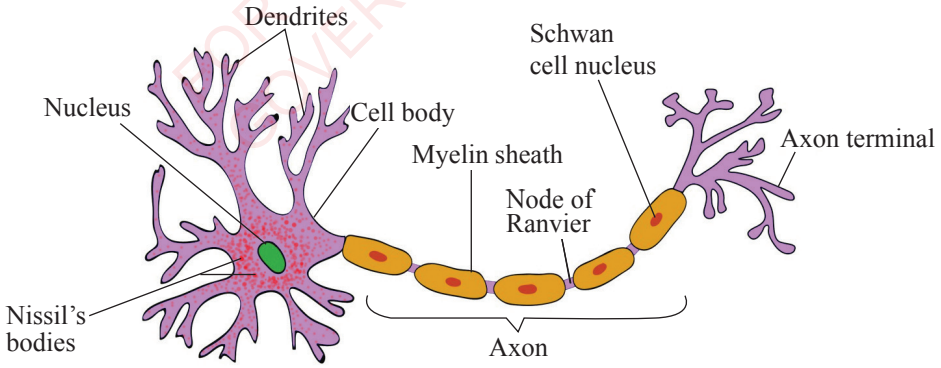


Figure 4.2 Structure of a typical neurone

Neurones are supported, protected, and nourished by non-neuronal cells of the nervous system, which are known as glial cells. Together with extracellular tissue, glial cells make up the neuroglia. Some neuroglias are phagocytic cells that remove bacteria and debris from the neurones while others provides metabolic and structural support.

Types of neurones

Based on their function and structure there are three types of neurones; which are sensory neurones, intermediate neurones (interneurones), and motor neurones.

Sensory neurones (Afferent neurones)

Sensory and intermediate neurones are also known as afferent neurones. These are neurones with long dendrites and short axon. The cell body and dendrites of the sensory neurones mostly lie outside the brain and spinal cord. Sensory neurones transmit nerve impulses from sensory receptors to the CNS (Figure 4.3) for the interpretation.

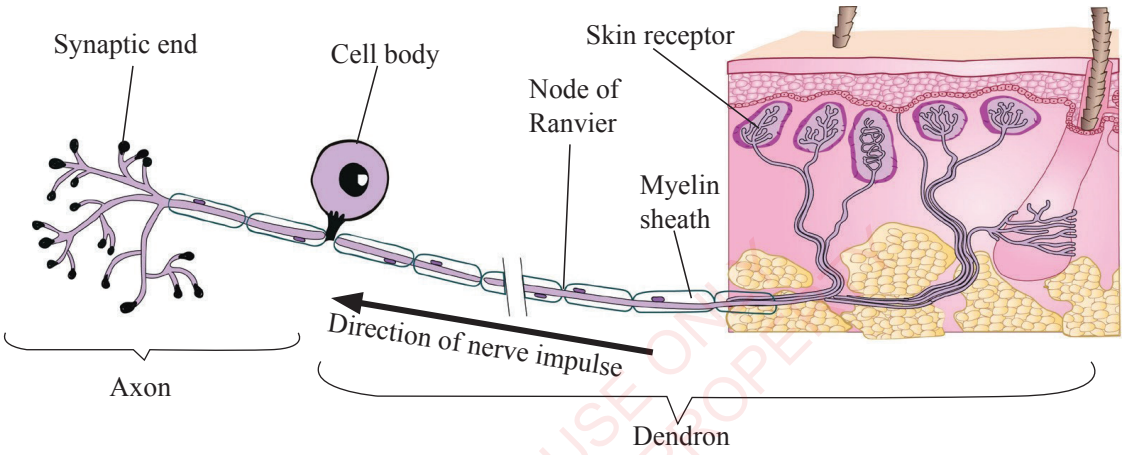


Figure 4.3 Structure of a sensory neurone

Interneurones (Intermediate neurones)

These are also known as connector neurones or relay neurones (Figure 4.4). They are much smaller nerve cells with many interconnections. Interneurones have short dendrites and short or long axons. They lie entirely within the CNS (brain and spinal cord). They transmit nerve impulses within the CNS; that is, they relay information between sensory and motor neurones. The sensory neurones and intermediate neurones both carry impulses towards the CNS.

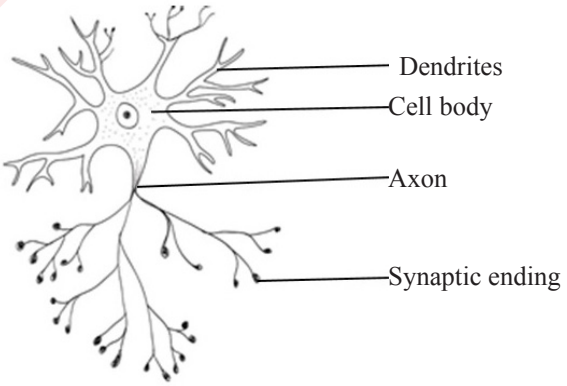


Figure 4.4 Structure of an intermediate neurone

Motor neurones (Efferent neurones)

Motor neurone have short dendrites and long axons; their dendrites and cell bodies are located in the CNS; and the axon is outside the CNS. Motor neurones transmit nerve impulses from the CNS to the effector organs such as muscles or glands, which eventually respond to the stimulus (Figure 4.5). Axon always transmits impulses away from the cell body while dendron carries impulses towards the cell body.

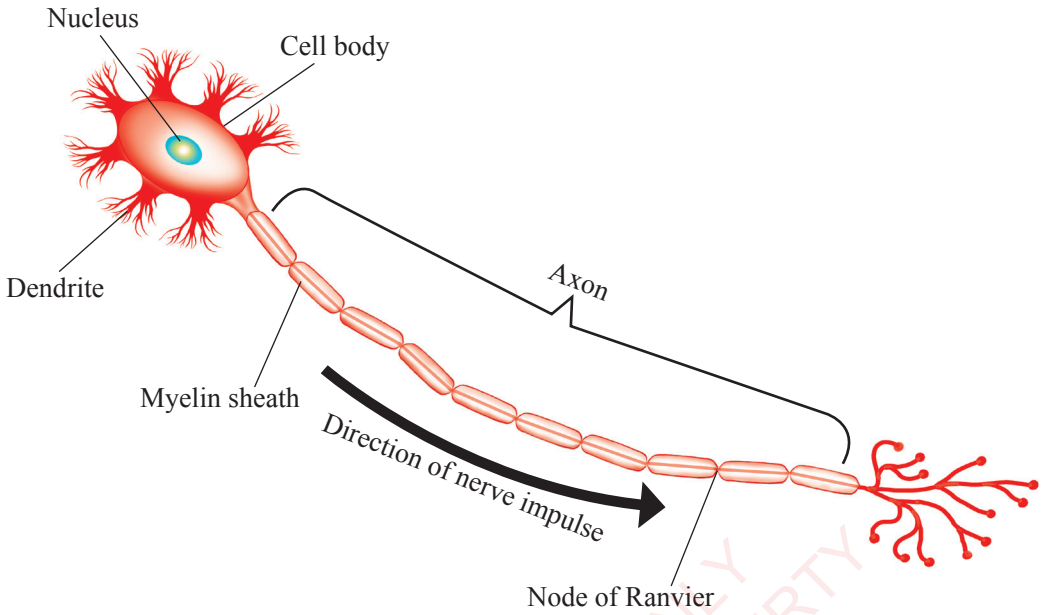


Figure 4.5 Structure of a motor neurone

Classification of neurones based on the number of dendrites

Neurones can also be classified on the basis of the number of their dendrites arising from the soma (cell body). In this classification, there are three main types of neurones. These include unipolar, bipolar and multipolar neurones. Unipolar neurones have a single short dendrite terminating onto bush-like tufts or dendrites. These are found in the granular layer of the cerebellum. Bipolar neurones are sensory neurones that have two processes coming from the cell body; one dendron and one axon. Bipolar sensory neurones are found in the retina of the eye, ganglia of the vestibulocochlear nerve and the olfactory epithelium. Multipolar neurones have three or more processes coming from the cell body. They possess one axon and two or more dendrites. Multipolar neurones form the major part of the CNS. They include interneurones and motor neurones. (Figure 4.6).

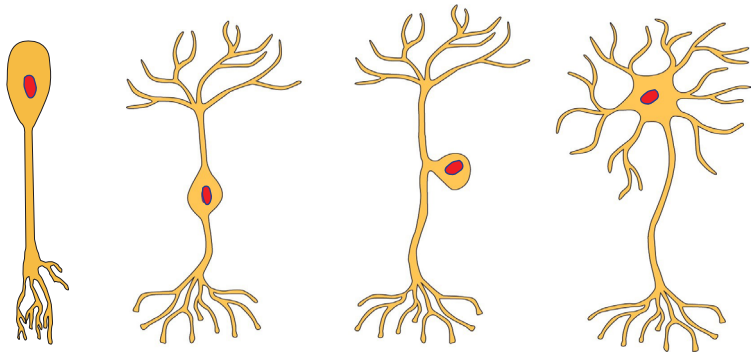


Figure 4.6 Structural classification of neurones (a) unipolar (b) bipolar (c) pseudo unipolar and (d) multipolar

Exercise 4.1

1. Describe the structure of the nervous tissue.
2. Explain the adaptive features of the nervous tissue.
3. With the help of diagrams, describe the types of neurones.

Nerve impulses

A nerve impulse is an electrical signal that travels along the axon. It is generated when the nerve cell is activated. Movement of ions in and out of the neurone causes a sudden change in the voltage across the wall of the axon. This triggers a wave of electrical activity that passes from the cell body along the length of the axon to the synapse.

Resting potential

This occurs when the neurone is at rest. In an inactive neurone, the axoplasm is negatively charged with respect to the outside of the cell. The difference in electrical charge is maintained by active transport of sodium ions out of axoplasm. A cell in this state is said to have a resting potential and it is polarised. At this state, the potential difference existing across the cell surface membrane inside the cell with respect to the outside part is negative, which is about -70 mV. At this time, the axon does not conduct any impulse. The cytoplasm inside the axon has a high concentration of K^+ and low concentration of Na^+. This is contrary to the outside part which has a low concentration of K^+ and high concentration of Na^+. The resting potential is maintained by active transport and passive diffusion of ions. It is active transport of ions against the electrochemical gradient of sodium/potassium (Na^+/K^+) pump. These are carrier substances located in the cell surface membrane. They are driven by energy supplied by ATP (Figure 4.7). The rate of diffusion is characterised by the permeability of the axon membrane to the ion. The K^+ has membrane permeability of about 20 times greater than that of Na^+.

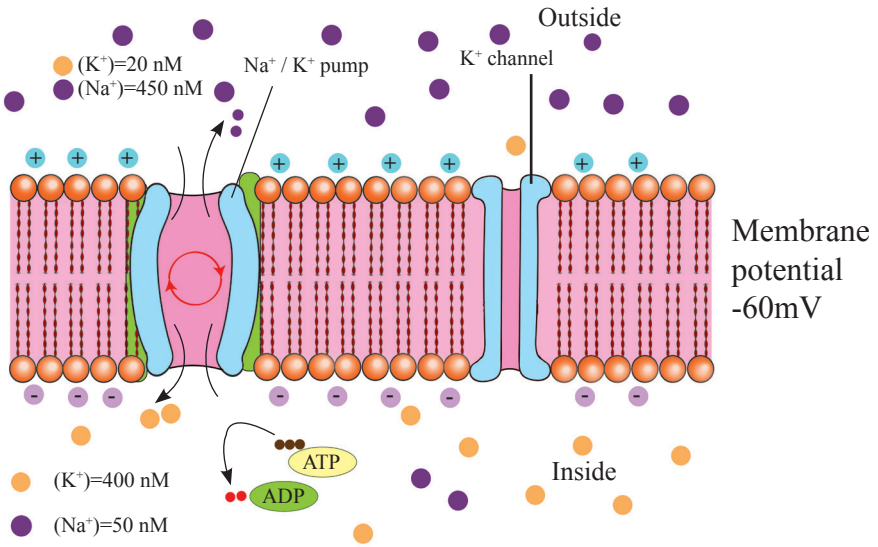


Figure 4.7 A membrane at resting potential (Polarised membrane)

Action potential

An action potential is a rapid, temporary change in membrane potential. It may qualify as the most important type of electrical signal in cells. In a neurone, action potential is generated by special types of voltage-gated ion channels embedded in cell's plasma membrane. A neurone displaying the nerve impulse is said to have an action potential and the cell is depolarised. Stimulation of axon by electrical impulse may result into a change in potential difference of about +40 mV across the axon membrane, from more negative inside to more positive inside.

Action potential is generated by a sudden opening of sodium channels. This occurs in response to stimulus which brings about a slight depolarisation or loss of charge of the axon membrane. Opening of Na^+ gates increases permeability of the axon membrane to sodium ions which enter the axon by diffusion. This increases the number of positive ions inside the axon, which consequently becomes more depolarized. Since sodium gates are sensitive to depolarization, the greater the depolarization, the more sodium gates are open, allowing more sodium ions to enter into the cell, hence greater depolarization and this is called a positive feedback loop. Positive feedback loop causes acceleration in the entry of sodium to the potential difference peaks at about +40 mV. This peak corresponds to the maximum concentration of sodium inside the axon. The total depolarization associated with the action potential has therefore been from -70 mV to +40 mV. The action potential has the following three distinct phases:

a) Depolarisation

This is the decrease in voltage across the membrane. It occurs when there is a stimulus that leads to the opening of the sodium channel to increase inflow of sodium ions. The process makes the inside of the cell less negative.

b) Rapid repolarisation

This is the process that changes the membrane potential back to negative inside and positive outside. A fraction of a second after the sodium gates open, depolarisation of the axon membrane causes the potassium gates to open too, and potassium diffuses out of the cell. Since potassium is positively charged, the inside of the cell becomes less positive and starts the process of repolarisation, then, it returns to its original resting potential.

c) Hyperpolarisation

This occurs after the impulse has been transmitted; the action potential falls down and the sodium gates close immediately. But potassium gates delay to close, causing more K^+ ions to exit the axon and this makes the membrane slightly more negative than the resting potential. Hyperpolarisation of the axon overshoots into more negative potential than the original potential.

All the three phases of the action potential occur within few milliseconds (ms) for the action potential to begin in a giant axon, the membrane potential must shift from its resting potential of -70 mV to about +40 mV. If the membrane depolarises less than that, an action potential does not occur. However, if this threshold potential is reached, sodium ion channels in the axon membrane open. Ions, thus rush into the axon following their electrochemical gradients. The inside of the membrane becomes less negative and then positive with respect to the outside. When the membrane potential reaches about +40 mV, a rapid change occurs and the repolarisation phase begins (Figure 4.8). The change is caused by the closure of sodium ion channels and the opening of potassium ion channels.

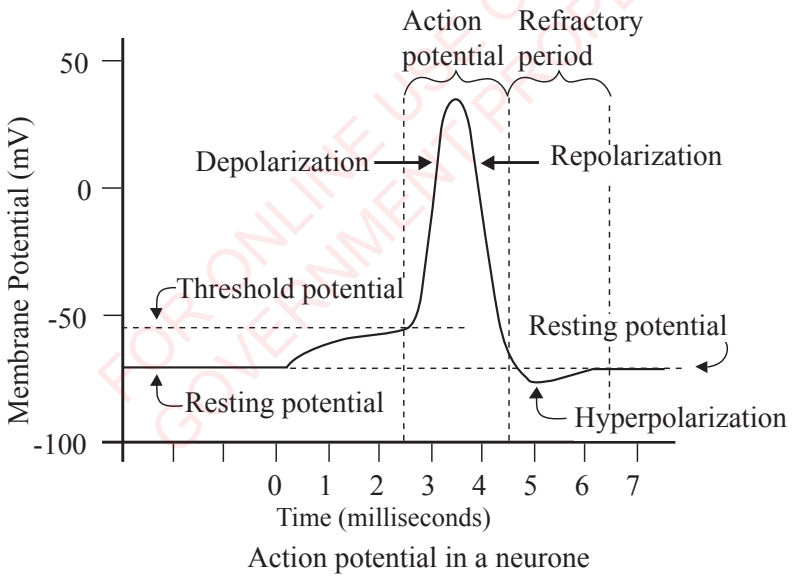


Figure 4.8 Graph showing the propagation of nerve impulse across a membrane

In summary, an action potential occurs due to opening or closing of specific channels in the plasma membrane in response to changes in voltage. An action potential always has the same three-phase form; even though the size of the resting potential, threshold potential, and peak depolarization may vary among the species or even among different types of neurones in one species.

Conduction of nerve impulse along the axon

The mechanism for impulse transmission along the axon involves the following steps:

a) Polarization of the neurone's membrane

Sodium is in high concentration on the outside, whereas potassium is in high concentration on the inside. Cell membranes surround neurones, like any other cell in the body which has a membrane. When a neurone is not stimulated, just sitting with no impulse to carry or transmit, its membrane is said to be polarised. Being polarized means that the electrical charge on the outside of the membrane is positive while the electrical charge on the inside of the membrane is negative (Figure 4.9).

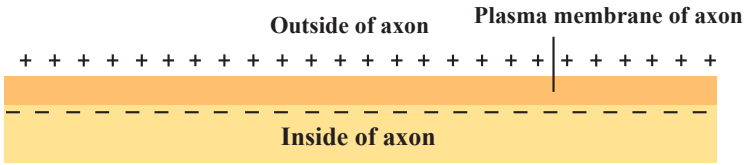


Figure 4.9 Polarised axon membrane

b) The resting potential gives the neurone a break

When the neurone is polarised, it is said to be at its resting potential. It remains in this state until when the stimulus comes along (that is, when it is stimulated). When action potential is initiated, a region of the membrane depolarises. As the result the adjacent region becomes depolarised as well (Figure 4.10).

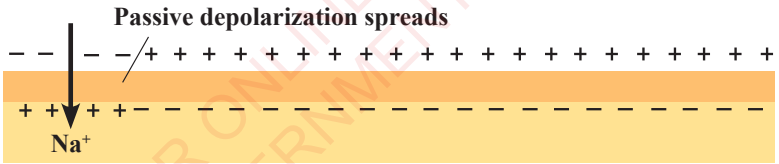


Figure 4.10 Propagation of nerve impulse across a membrane (depolarization)

c) Action potential

Sodium ions move inside the membrane when a stimulus reaches a resting neurone. The gated ion channels on the resting neurone's membrane open suddenly to allow the Na+ that was on the outside of the membrane to rush into the cell. While this happens, the neurone changes from being polarised to being depolarised. After more positive ions enter inside the membrane, the inside becomes positive and polarisation is removed and the threshold is reached (Figure 4.11).

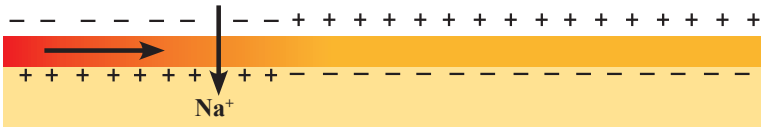


Figure 4.11 Propagation of nerve impulse across a membrane (action potential)

d) Repolarisation

Localised electrical circuits are established, causing further influx of sodium ions and so progression of the impulse. Behind the impulse, potassium ions begin to leave the axon along the concentration gradient, hence repolarisation beginning to occur due to the outward flow of K^+ ions. The depolarisation speeds forward, triggering an action potential (Figure 4.12).

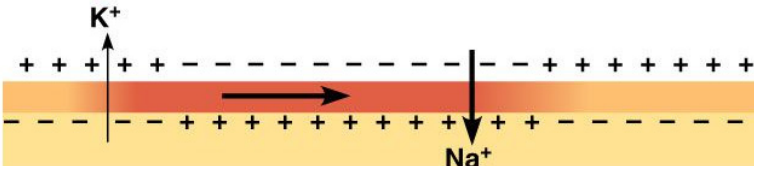


Figure 4.12 Propagation of nerve impulse across a membrane (localization)

During repolarisation, potassium ions move outside, while sodium ions stay inside the membrane. After repolarisation, the inside of the cell becomes flooded with Na^+; the gated ion channels on the inside of the membrane open to allow K^+ to move to the outside of the membrane. With K^+ moving to the outside, the membrane's repolarisation restores electrical balance, although it is the opposite of the initial polarised membrane that had Na^+ gates close. Otherwise, the membrane could not repolarize (Figure 4.13). Then Na^+ ions are actively forced out of the axoplasm in the process called sodium pump. However, since K^+ ions are also involved in this process, the process is best called cation pump.

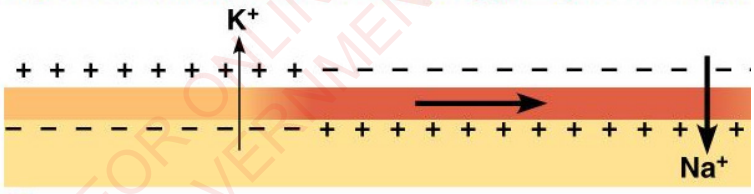


Figure 4.13 Propagation of nerve impulse across a membrane (repolarization)

Characteristics of nerve impulses

Nerve impulses have the following characteristic features:

a) Transmission speed

Impulses are always transmitted at a very high speed. Depending on the nature of a nerve cell, the speed of transmission varies from 0.5 to 100 metres per millisecond. The speed of impulse transmission is determined by body temperature, axon diameter, and presence of myelin sheaths.

i) Body temperature

The speed of impulse transmission depends on the body temperature of the organism, such that, the speed of impulse transmission in homoeothermic organsms is greater than in poikilothermic organisms.

ii) Axon diameter

The greater the axon diameter the higher the transmission speed. This is because increased axon diameter minimizes the resistance of the axoplasm.

iii) Presence of myelin sheaths

Axons with myelin sheaths conduct impulses at higher speed than those without sheaths. The myelin sheath allows impulses to leap from one node of ranvier to another, thereby increasing transmission speed (Figure 4.14). This is the saltatory conduction.

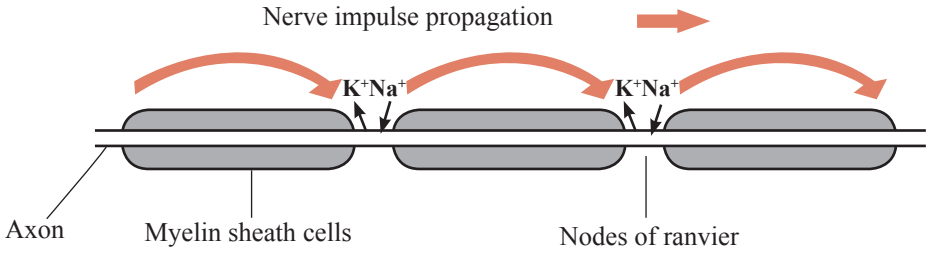


Figure 4.14 Leap of impulse from one node of Ranvier to another in a myelinated axon

b) Unidirectionality

Impulses always flow in only one direction, that is, from cell body to terminal dendrites in the neurone, or from pre-synaptic to post – synaptic neurone across a synapse.

c) Refractory period

During this period, a part of an axon is unable to conduct a new impulse immediately after propagation of an action potential. The resting potential is restored by outward movement of K^+ ions and prevention of inward movement of Na^+ ions.

Furthermore, the refractory period is divided into two phases namely; absolute refractory period and relative refractory period. Absolute refractory period lasts for 1 ms. In this period, a part of an axon is unable to propagate an action potential regardless of the strength of the stimulus. The relative refractory period lasts for 5 ms. During this period, the impulse can be propagated if its strength exceeds a threshold value. The significance of the refractory period is to ensure unidirectional flow of impulse and to separate one action potential to the next.

d) All-or-nothing law

According to this law, for the action potential to be propagated, the stimulus applied should exceed a threshold value. The threshold value is the minimum energy level, and when reached, the action potential will be generated. However, the size of the action potential will not decrease as it is transmitted along the

neurone, but it will always remain the same. In other words, the action potential is both generated and kept the same or not generated if the threshold value is not exceeded.

e) Propagation (Conduction)

A nerve impulse is conducted as a wave of depolarisation that moves along the surface of the nerve cell. This means that progressive depolarisation of the axon membrane leads into impulse transmission**.**

Structure of a chemical synapse

The point where the axon of one neurone joins the dendrite or cell body of another neurone is known as a synapse. The membrane of the first neurone connecting to the synapse is called a presynaptic membrane while the other membrane of the next neurone is called a postsynaptic membrane. These membranes between the two neurones are separated by a gap of about 20 nm called the synaptic cleft. At the end of the presynaptic neurone, there is a bulge called synaptic knob.

The cytoplasm of the synaptic knob contains numerous mitochondria and small synaptic vesicles. Transmission across a synapse is carried out by chemical substances called neurotransmitters; which are stored in synaptic vesicles. The presynaptic membrane is modified for the attachment of synaptic vesicles and the release of transmitter substance into the synaptic cleft. The postsynaptic membrane contains large protein molecules, which act as receptor sites for the transmitter substances and numerous channels and pores for the movement of ions into the postsynaptic neurone (Figure 4.15).

The neurotransmitter substance is either produced by the cell body of the neurone or synaptic knob. These substances are synthesised by enzymes stored in the cell body. The neurotransmitters allow the transmission of signals from one neurone to the next across synapses. There are many types of neurotransmitters, and these include acetylcholine, norepinephrine, serotonin, dopamine, and glutamate. The two common neurotransmitters in vertebrates are acetylcholine (Ach; an ammonium compound) and norepinephrine (also called noradrenaline). Neurones using acetylcholine as a neurotransmitter are described as cholinergic neurones, while those using norepinephrine (noradrenaline) are called adrenergic neurones. Norepinephrine is released in the sympathetic nervous system by some nerves, while acetylcholine is released by all nerves except some nerves in the brain.

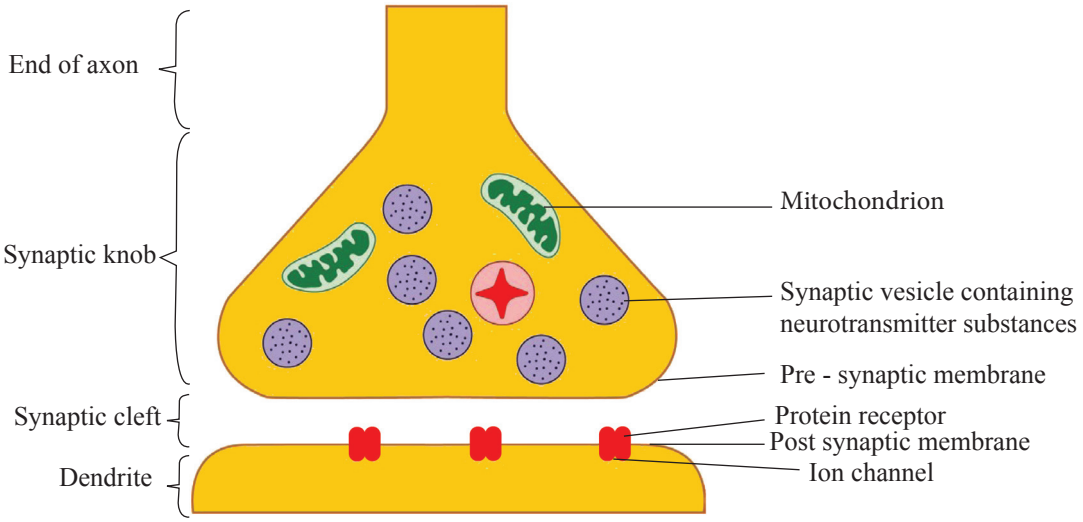


Figure 4.15 Structure of the chemical synapse

Synaptic transmission of nerve impulses

The nerve impulse passes down the dendrite, through the cell body, and down the axon. At the end of the axon, the impulse encounters a fluid-filled space separating the end of the axon from the dendrite of the next neurone or from a muscle cell. This space is called the synapse. The synapse located at the junction of a neurone and muscle fibre is called a neuromuscular junction. Such synapses can be classified based on their means of transmission of impulses across their gaps. In this typology, two types are revealed, namely electrical and chemical synapses. An electrical synapse is the one in which the physiological continuity between pre and post synaptic neurones is provided by a special channel called a gap junction between the two neurones. These channels are capable of passing an electrical current, causing voltage changes in the pre synaptic cell to induce voltage changes in the post synaptic cell. This synapse can be effective when the neurones are very close together (2 nm). The main advantage of electrical synapse is that it facilitates the rapid transfer of signals from one cell to the next. In chemical synapses, impulse transmission is facilitated by chemical substances called neurotransmitters.

Mechanism for synaptic transmission

a) An action potential arrives at the end of the axon and induces changes in the cell membrane (Figure 4.16).

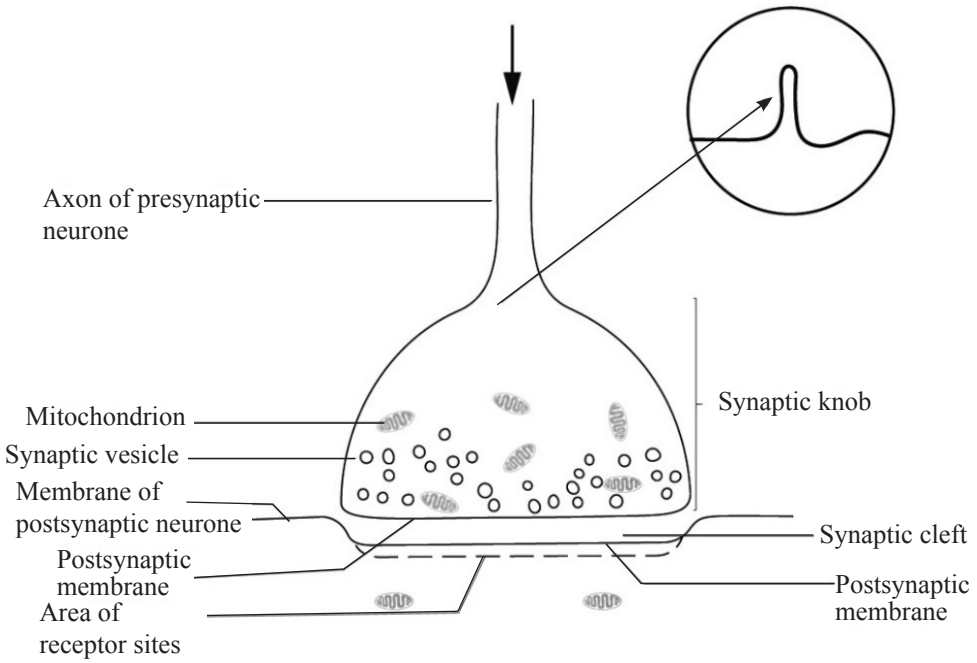


Figure 4.16 Conduction of nerve impulses at the presynaptic knob and action potential

b) Depolarisation at the synaptic knob after arrival of nerve impulses create the action potential which opens voltage-gated calcium channels located near the synapse in the presynaptic membrane, thus increasing the permeability of the membrane to calcium (Ca^{2+}) ions. The electrochemical gradient for Ca^{2+} results in the inflow of calcium ions through the open channels (Figure 4.17).

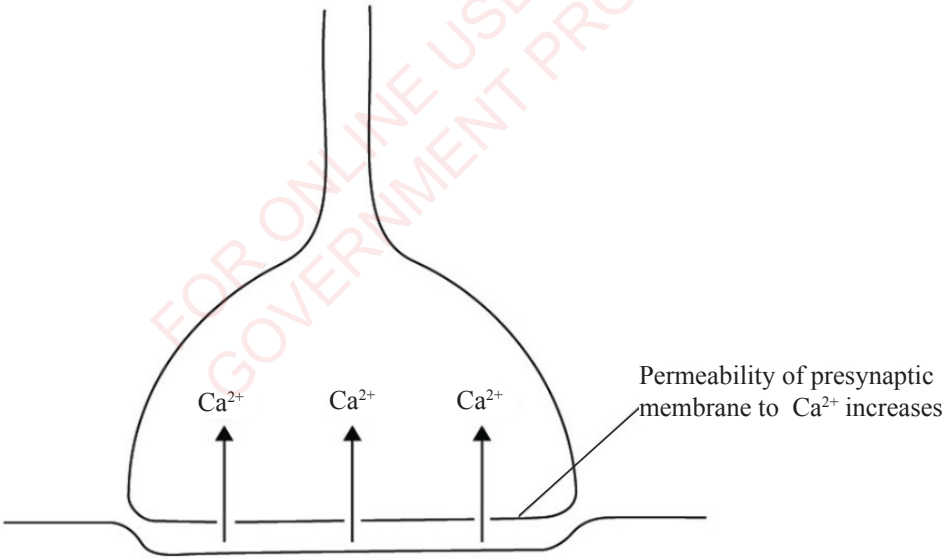


Figure 4.17 Permeability of presynaptic membrane to the calcium ions

c) In response to the increase of calcium concentration inside the axon, synaptic vesicles fuse with the presynaptic membrane and release neurotransmitters into the gap between the cells which is called the synaptic cleft. The delivery of neurotransmitters into the cleft is an example of exocytosis (Figure 4.18).

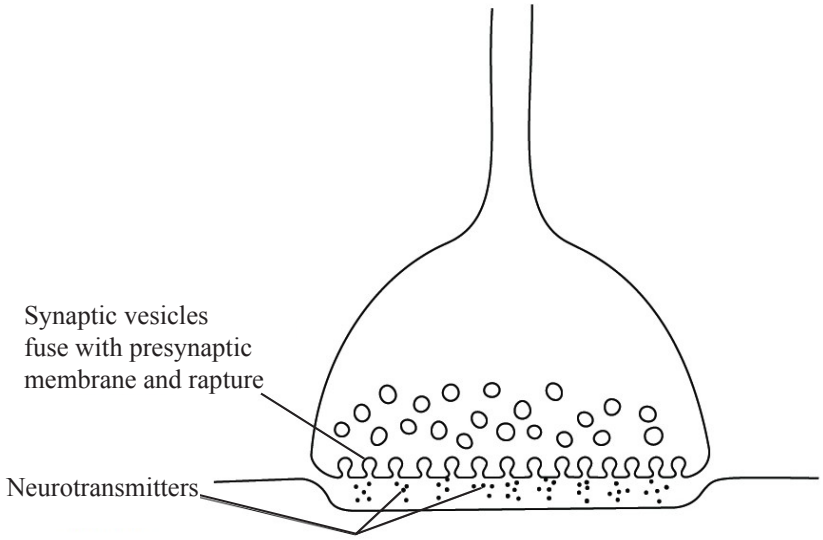


Figure 4.18 Presynaptic membrane fused with synaptic vesicles

d) The vesicles then return to the cytoplasm and are refilled with transmitter substance. The neurotransmitter diffuses across the synaptic cleft, a process which takes 0.5ms per synapse. Upon reaching the postsynaptic membrane, it binds with receptor molecules which recognise the molecular structure of the acetylcholine molecule (Figure 4.19).

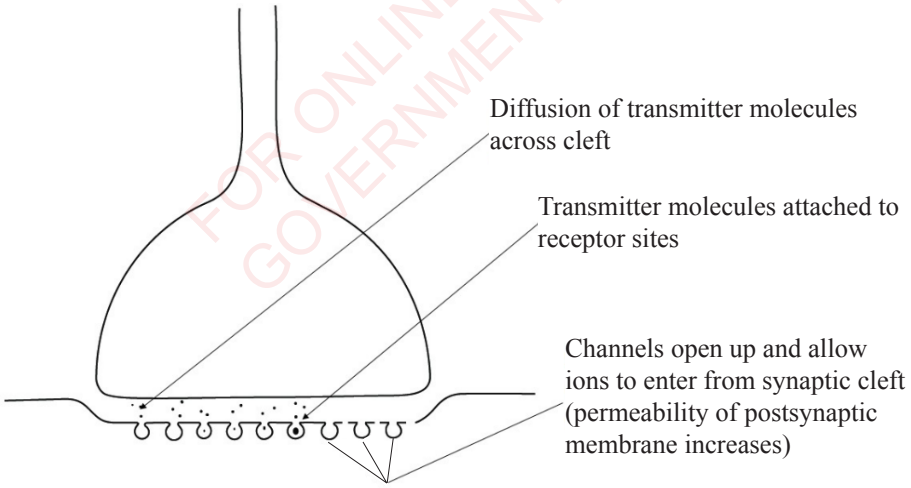


Figure 4.19 Transmitter molecules attached to receptor sites on postsynaptic knob

e) The arrival of acetylcholine at the postsynaptic membrane changes the shape of the receptor site. This initiates ion channels to open up. The excitatory synapse which opens ion channels on the postsynaptic membrane allowing sodium ions to enter and potassium ions to leave. This creates a new potential known as the excitatory postsynaptic potential in the post synaptic neurone. Once the neurotransmitter has depolarised the post synaptic neurone, it is hydrolysed to form acetyl and choline by the enzyme "acetylcholinesterase" which is found in the postsynaptic membrane. This prevents the successive impulse merging at the synapse (Figure 4.20).

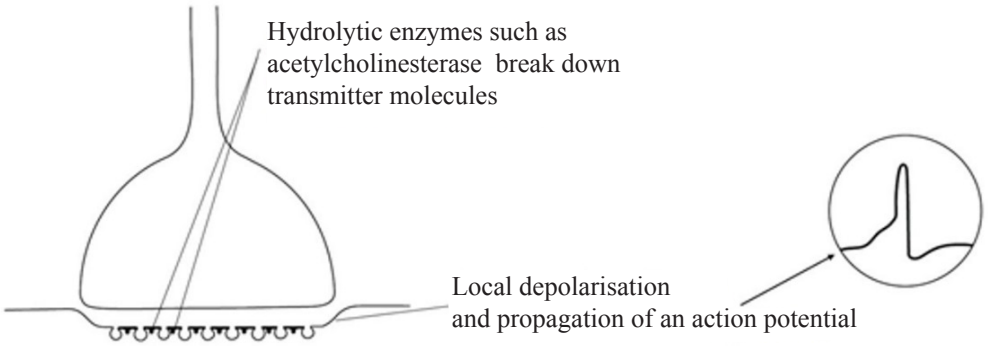


Figure 4.20 Local depolarisation and propagation of an action potential in postsynaptic membrane

The resulting acetyl and choline diffuses across the synaptic cleft into the synaptic knob of the presynaptic neurone where they get stored in their vesicles for further use. The process is facilitated by energy produced by numerous mitochondria in the knob. The overall depolarising effect of several Excitatory Postsynaptic Potential (EPSPs) is called summation. When two or more EPSPs simultaneously arising at different regions either on the same or different neurones, producing sufficient depolarisation which can starts an action potential in the postsynaptic neurone, the phenomenon is known as spatial summation.

The excitatory postsynaptic potential builds up as more neurotransmitter substance arrives until sufficient depolarisation occurs to exceed the threshold value and so generate an action potential in the postsynaptic neurone, this is called temporal summation. All events described are for excitatory synapse, some known inhibitory synapses respond to neurotransmitter by opening potassium ion channels and leaving the sodium ion channels closed. Potassium, therefore, moves out causing the membrane to be polarised; consequently, it prevents the threshold value to be exceeded. Thus no action potential will be created.

Functions of synapses

a) They transmit information between neurones. The synapses pass impulses in one direction only. Such impulses are transmitted at the presynaptic membrane and received by the postsynaptic membrane, which

ensures one direction of flow along a given pathway.

b) They amplify impulses by acetylcholine which is released at a neuromuscular junction which excite the post synaptic membrane and amplifies any weak impulse arriving. Repeated low level stimuli can be amplified as each impulse is arriving at the synapse, causing the release of more neurotransmitter, resulting in one larger impulse in the postsynaptic neurone. Therefore, this allows the body to respond to the stimuli more effectively.

c) They act as junctions that transmit electric nerve impulses between neurones, or between neurone and effector cells. A synaptic connection between a neurone and muscle cell is known as neuromuscular junction.

d) They filter out low level stimuli; as more neurotransmitter diffuses across the synaptic cleft, the excitatory postsynaptic potential increases. For the impulses to be generated in the postsynaptic neurone, it must reach the action potential of about +40 mV. This implies that weak impulses in the presynaptic neurone do not cause enough neurotransmitter to be released for an action potential in the postsynaptic neurone to be generated. As a result, synapses are able to filter out low level stimuli that the body does not need to respond, that is a way of conserving energy.

e) They allow adaptation to intense stimulation and fatigue. The amount of transmitted substance which is released by synapse steadily falls off in a response to a constant stimulation until the supply of the transmitted substance is exhausted.

f) They allow convergence, spatial summation and integration of the stimuli. In convergence of the stimuli, the postsynaptic nerves receive impulses from a large number of excitatory and inhibitory presynaptic neurones. In a spatial summation postsynaptic neurone is able to sum-up the stimuli from all presynaptic neurones, where the synapse act as a centre for the integration of stimuli from different sources; hence produces the coordinated response.

Exercise 4.2

1. Explain the following concepts:
   a) Action potential
   b) Resting potential
   c) Polarization
   d) Depolarisation of nerve cells
2. Describe the formation and conduction of nerve impulses along the axon.
3. Outline the characteristics of nerve cells.
4. Using clear illustrations, describe the synaptic transmission of nerve impulses.
5. State the role of synapses in the nervous system.

4.2 Sensory receptor

The receptor is a cell or a nerve ending or a group of nerve endings specialised for reception of stimuli and change specific stimuli into nerve impulse. The ability of receptors to convert stimuli or events which occur in the environment into a nerve impulse is known as transduction. The structures which transform stimulus energy into electrical responses which is the nerve impulses in axons are called transducers. Receptors are therefore biological transducers that convert energy from both external and internal environments into electrical impulses. They may be grouped together to form a sense organ, such as the eye or ear, or they may be scattered, as in those of the skin and viscera. The coordinated activity of an organism relies upon a continuous input of information from internal and external environments. When the information received leads to a change in activity or behaviour of the animals, it is called stimulus. The specialised region of the body which has the ability of detecting the stimulus is known as sensory receptor.

Types of sensory receptors

Receptors can be classified into different groups based on their structure, type, and the location of stimuli they detect.

a) Classification of sensory receptors based on structure

Based on their structure there are two types of receptors, and these are: single sensory neurone receptors and complex receptors (sense organs).

Single sensory neurone receptor

These receptors are simple and mostly primitive. They consist of a single sensory neurone which is capable of detecting the stimulus and giving rise to a nerve impulse passing to the central nervous system. Examples include: skin mechanoreceptors in the pacinian corpuscles.

Complex receptors

These sense cells consist of modified epithelial cells. They can detect stimuli. Sensory cells, sensory neurones, and other associated or accessory structures are examples of complex receptors. The cones, rods, lens and iris (in the eye) are examples of sense cells.

b) Classification of sensory receptors based on type of stimuli

Based on the type of stimulus they detect in the environment, there are several types of sensory receptors, which include: mechanoreceptor, photoreceptor, thermoreceptor, nociceptor, chemoreceptor, osmoreceptor and electroreceptors.

Mechanoreceptors

They detect mechanical stimuli which are caused by mechanical forces such as sound or vibration, touch, pressure, and gravity. Touch receptors are found all over the body. Other touch receptors include Merkel's discs and Meissner's corpuscles which detect light and pacinian corpuscles which sense deep pressure and vibration. Mechanoreceptors are responsible for detecting changes that are perceived such as sound or touch. They are also responsible for maintaining equilibrium balance and proper tone in muscles and joints (Figure 4.21).

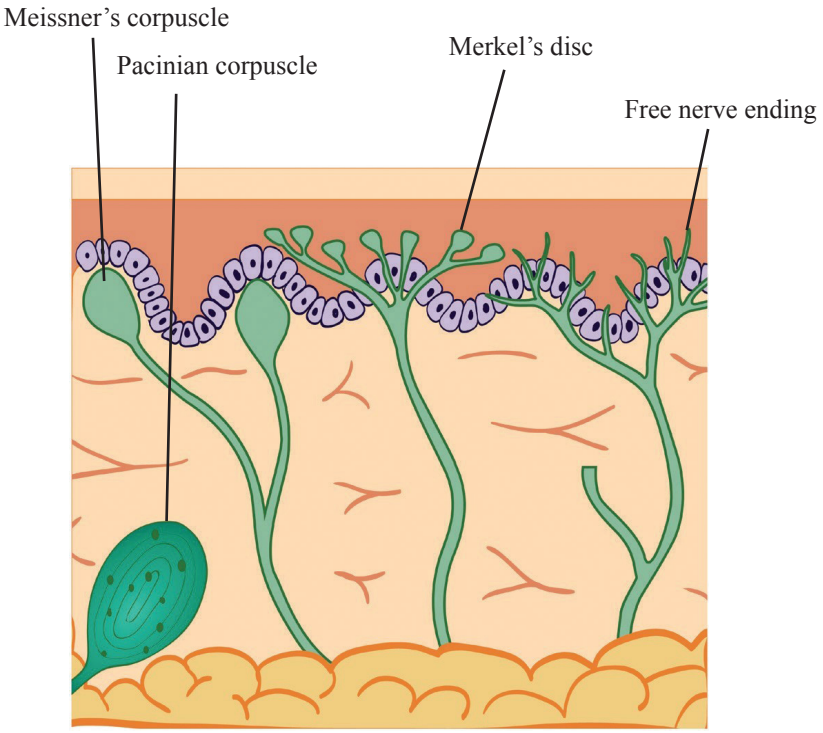


Figure 4.21 Structure of the touch receptors

Photoreceptors

These are receptors which detect electromagnetic stimuli such as light. There are two types of photoreceptors namely; rods and cones. These are found in the retina of an eye for detecting dim and bright light respectively (Figure 4.22).

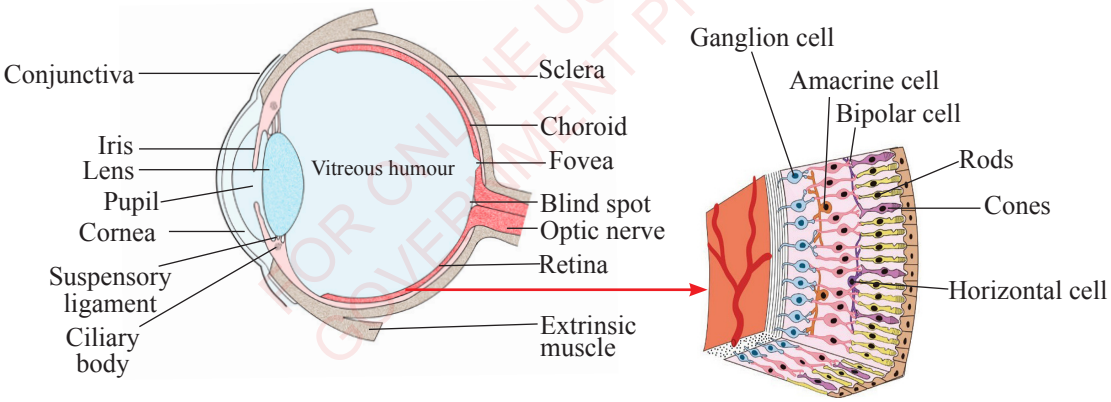


Figure 4.22 Structure of the photoreceptors

Thermoreceptors

Thermoreceptors are specialised nerve cells or receptors that can detect differences in temperature. They can detect hotness (heat) and coldness (cold). They are thus of two types, heat and cold receptors. They are found throughout the skin to allow sensory reception throughout the body. The location and number of thermoreceptors determine the sensitivity of the skin to temperature changes. Examples of thermoreceptors are bulbs of Krauze which sense coldness and organ of Ruffin which detects heat. These cells are connected to heat gain and heat loss centres of the hypothalamus.

Nociceptors (pain receptors)

These are receptors that can detect pain and they are found in the skin, muscles, bones, blood vessels, and some organs (4.23).

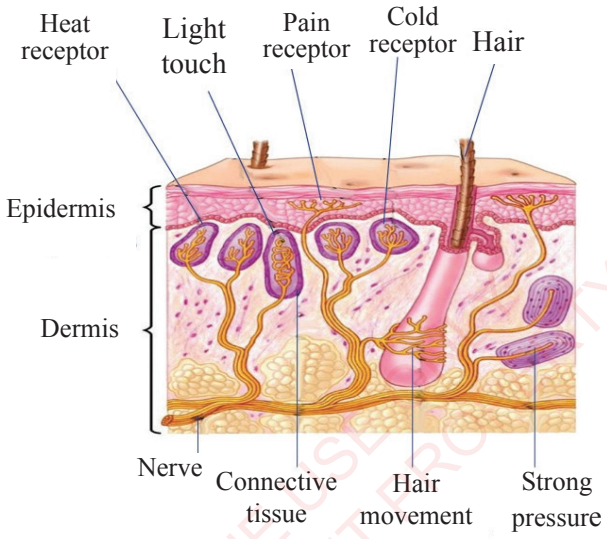


Figure 4.23 Sensory receptors of the skin

Chemoreceptors

These are receptors which detect chemical stimuli such as smell, taste, and humidity. They have the ability to respond to a diverse range of chemical substances in food, nasal passage, and blood. For example, olfactory receptors in the roof of the nasal cavity can be stimulated by odours. Nerve impulses from these receptors travel to the olfactory bulb (Figure 4.24). When odour molecules enter the nose, they stimulate the olfactory cilia (tiny hairs) attached to receptor cells, causing nerve impulses to pass to the olfactory bulb and then to the brain.

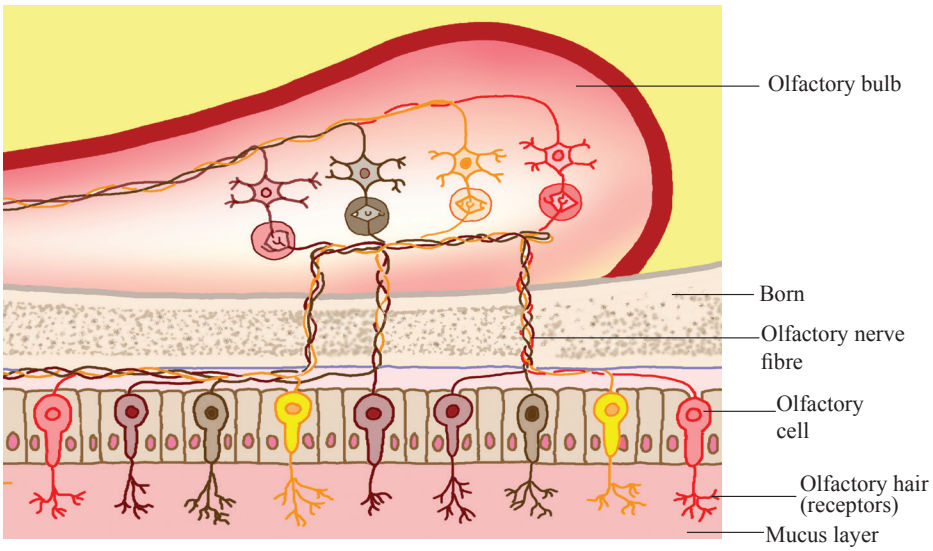


Figure 4.24 Structure of the olfactory lobe

Taste buds are located on the upper surface of the tongue. Each bud contains about 25 sensory receptor cells with tiny taste hairs exposed to drink and food dissolved in saliva (Figure 4.25). Such buds sense the five basic tastes: bitter, sour, salty, sweet, and umami (a savoury, meaty taste). A combination of odours and the basic tastes produce subtler tastes.

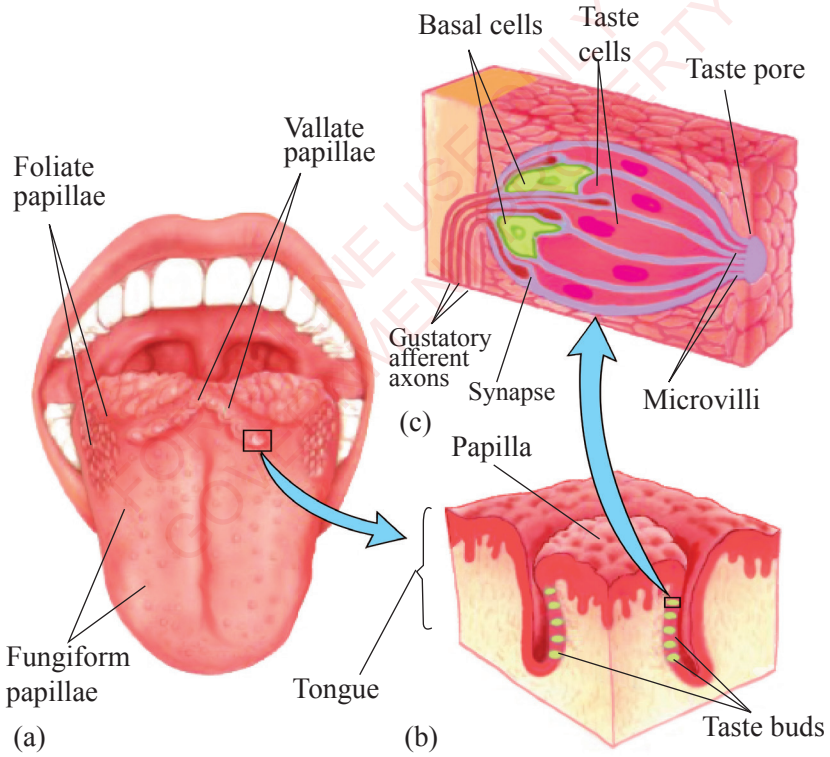


Figure 4.25 Structure of the taste receptors

Osmoreceptor

They detect the changes in osmotic pressure. The osmoreceptors are primarily found in the hypothalamus and kidney of most homoeothermic organisms. They contribute to regulate fluid balance in the body (osmoregulation) and modulate osmolarity in the kidney.

Electroreceptors

Electroreceptors detect natural electrical stimuli. They are almost found in aquatic or amphibious animals because salt water is a better conductor of electricity than air. The ampullae of Lorenzini are an example of electroreceptors in sharks. Some terrestrial organisms such as arachnids, cockroaches and bees are known to have electroreceptors.

c) Classification of sensory receptors based on the location of the stimuli they detect

Based on the location of stimulus they detect in the environment, three types of receptors; interoceptors, exteroceptors proprioceptors.

Interoceptors

These receptors detect stimulus which originates from the inside of the body; especially from internal organs and the gut. For example, stomach pain stimulus is detected by pain receptor (nociceptor) and blood pressure change stimulus is detected by pressure receptor (baroreceptor).

Exteroceptors

These are receptors which detect external stimuli such as light, temperature, olfactory and tactile. For example, the skin thermoreceptors detect the temperature changes of the external environment. Ear, eye and nose also detect stimuli that originate from external environment.

Proprioceptors

These are internal sensory receptors that monitor the degree of stretch of muscles and tendons around the body. This information gives an individual a sense of balance and awareness of the position of various parts of the body in relation to each other (Figure 4.26).

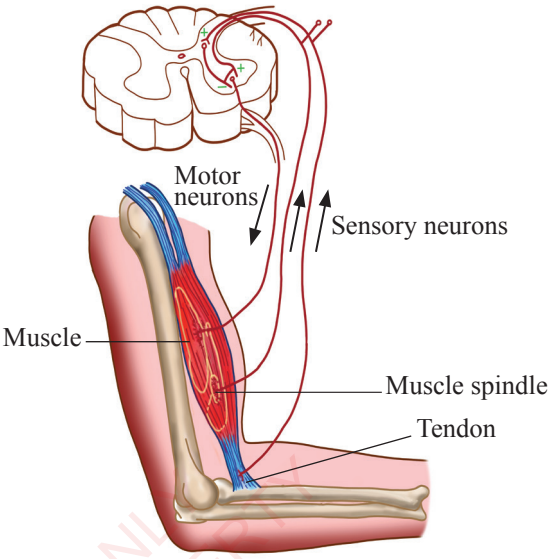


Figure 4.26 Structure of the proprioceptors

Mammalian eye

The eye is a sense organ which receives light of various wavelengths, reflected from objects at varying distances in the visual field and converts it into electrical impulses (Figure 4.27). Optic nerves transmit these impulses to the brain where an image of remarkable precision is perceived. The principal functions of the eye include: controlling the amount of light entering it, focusing images from the external world by means of a lens system, and processing the captured image into a pattern that can be seen.

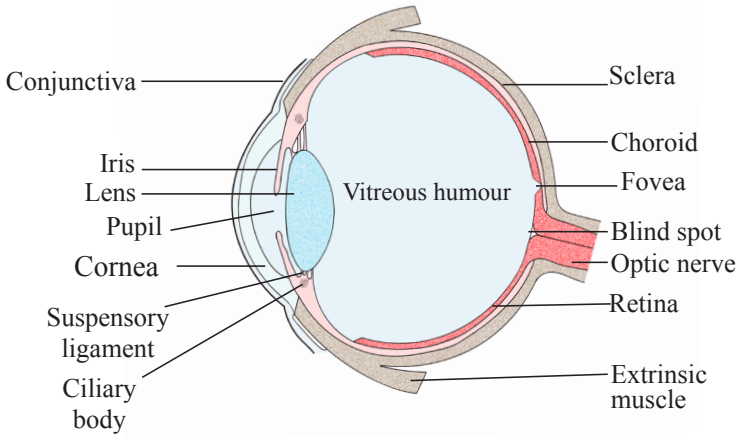


Figure 4.27 Vertical section of the human eye

Eye accommodation

This is the reflex mechanism by which light rays from an object are brought to focus on the retina. It involves two processes namely; reflex adjustment of the pupil's size and refraction of light rays.

Reflex adjustment of the pupil's size

This involves the control of the amount of light entering the eye, either bright light or dim light. In bright light, the circular muscles of the iris diaphragm contract, the radial muscles relax, the pupil becomes smaller, and less light enters the eye. This process prevents damaging the retina and increases the depth of focus. In dim light, the circular muscles of the iris diaphragm relax, the radial muscles contract, the pupil become large, and more light enters the eye. This decreases the depth of focus of the eye (Figure 4.28).

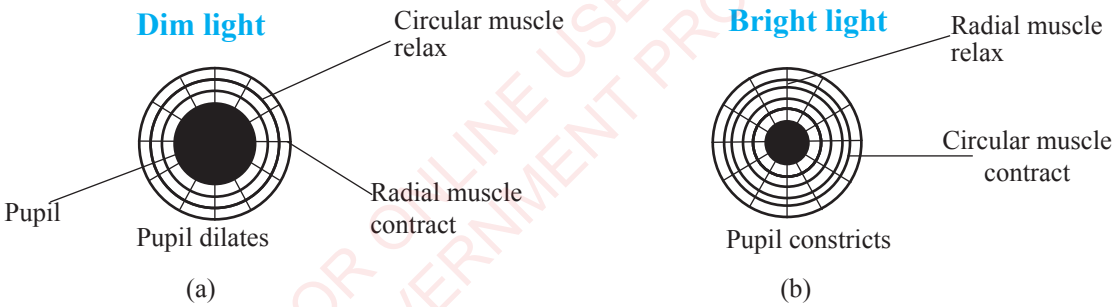


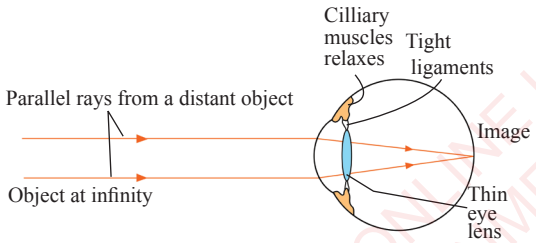
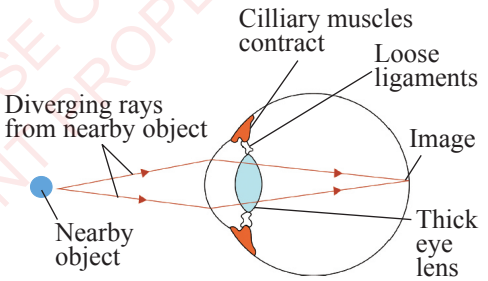
Figure 4.28 Reflex adjustment of the pupil's size in (a) dim and (b) bright light

Refraction of light rays

Refraction of light rays involves bending of light rays as they move through different media in the eye. At all distance range, light rays enter to the eye and refracted to come into exact focus on retina. Light rays from a distant object (more than 6m away), are nearly parallel to one another towards the eye while those from a closer object tend to spread out (diverging) as they make angle from the object. In all these two cases, light rays must be refracted or bent to focus on the retina.

Refraction is greater for light from near objects than for distant objects. The refraction is achieved at the air-cornea surface and at the lens when the light passes from one medium to another with a different refractive index. The function of the lens is to produce the final refraction that brings light to a sharp focus on the retina. The lens is elastic and changes the shape by the contraction and relaxation of the ciliary muscle which encircles it. This assists the lens in adjusting the light from both distant and near objects, which cannot be done by cornea. When the ciliary muscle contracts, the tension on the suspensory ligaments is reduced, and the lens fattens due to its elastic nature which increases the degree of refraction of light. When the ciliary muscles relax, the suspensory ligaments are stretched, pulling the lens outwards, making it thinner, and decreasing the degree of light refraction. Changing the shape of lens in different manners causes the lens to focus light rays from near and distant objects on the retina. This process is called accommodation. Light rays refraction in an eye at different distances is shown in Table 4.1.

Table 4.1 Refraction of light rays in human eye at different distances

Light from a distant object	Light from a nearby object
1. Parallel light rays reach the eye. 2. Cornea refracts (bends) light ray. 3. Circular ciliary muscle relaxes. 4. Suspensory ligament stretched. 5. The lens is pulled out. 6. Light focused on the retina.	1. Diverging light rays reach the eye. 2. Cornea refracts (bends) light ray. 3. Circular ciliary muscle contracted. 4. Suspensory ligament slacks. 5. The lens becomes more convex. 6. Light focused on the retina.
	

The structure of the retina

The retina is comprised of three layers of cells. The outermost layer is the photoreceptor layer containing rods and cones, partially embedded in the pigmented epithelial cells of the choroid layer. The rods and cones convert light energy into the electrical energy of the nerve impulse. The middle layer is an intermediate part which contains bipolar neurones with synapse, connecting the photoreceptor layer and the inner layer. Horizontal and amacrine cells are found in the middle layer. The innermost layer is an internal surface layer containing ganglion cells with dendrites in contact with bipolar neurones and axons of the optic nerve (Figure 4.29). It is important to note that cats and some nocturnal carnivorous mammals possess a reflective layer called

tapetum which is found behind the retina. This protein layer reflects light back into the eye and gives an opportunity for rod cells to absorb it. This character improves the vision of cats and nocturnals in dim light. The bright light shown by cats' eyes at night is the result of the reflection from the tapetum.

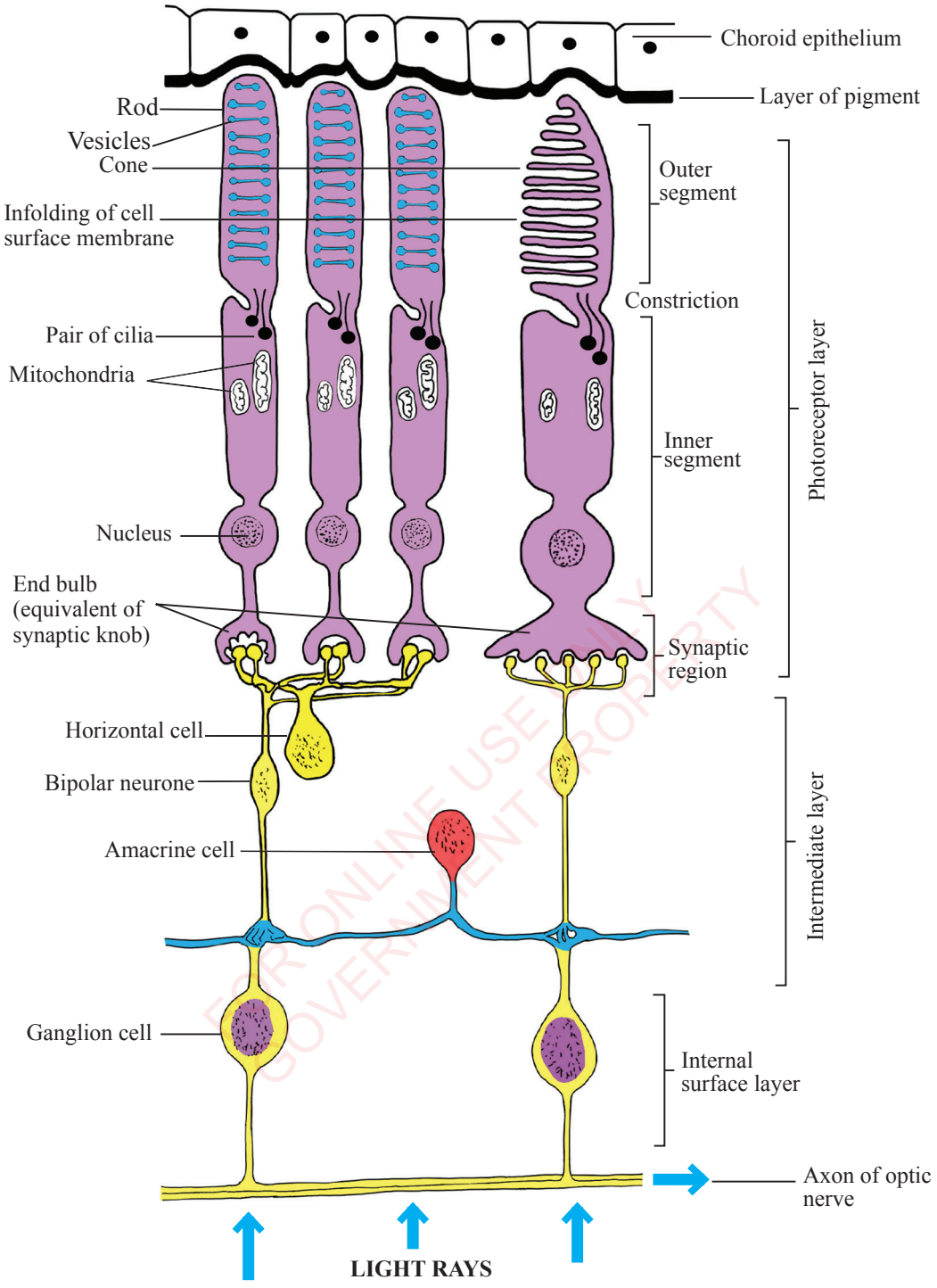


Figure 4.29 Structure of the retina

Structural differences between rods and cones

Rods and cones are generally similar in structure, but they differ in size and shape, as well as in the arrangement of the membranous discs in their outer segments. At the lowest levels of light, only rods are activated. Such rod mediated perception is called scotopic vision; the difficult of making visual discriminations under very low light conditions where only the rod system is active. The problem is primarily the poor resolution of the rod system and, to a lesser degree, the lack of perception of colour in dim light since such cones are not involved to a significant degree.

Although cones begin to contribute to visual perception at about the level of starlight, spatial discrimination is still very poor. As illumination increases, cones become increasingly dominant in determining what is seen. In addition, they are the major determinant of perception under relatively bright conditions, such as normal indoor lighting or sunlight. The contribution of rods to vision drops out nearly entirely in the so called photopic vision because their response to light saturates, that is, the membrane potential of individual rods no longer varies as a function of illumination because all of the membrane channels are closed. Mesopic vision occurs in levels of light at which both rods and cones contribute to vision at twilight. Thus, from these considerations, it should be clear that most of what we think of as "seeing" is mediated by the cone system. Thus, the loss of cone function is devastating, as it occurs in elderly individuals suffering from macular degeneration. Individuals who have lost cone function are blind, whereas those who have lost rod function only experience difficulty seeing at low levels of illumination (night blindness).

Differences in the transduction mechanisms of the two receptor types also contribute to the ability of rods and cones to respond to different ranges of light intensity. For example, rods produce a reliable response to a single photon of light, whereas more than 100 photons are required to produce a comparable response in a cone. Another difference is that, the response of an individual cone does not saturate at high levels of steady illumination, as does the rod response. Although both rods and cones adapt to operate over a range of luminance values, the adaptation mechanisms of the cones are more effective. This difference in adaptation is evident in the time course of the response of rods and cones to light flashes. The response of a cone, even to a bright light flash that produces the maximum change in photoreceptor current pick up is about 200 ms; which is more than four times faster than rod recovery.

The arrangement of the circuits that transmit rods and cones information to retinal ganglion cells also contributes to the different characteristics of scotopic and photopic vision. In most parts of the retina, rods and cones signals converge on the same ganglion cells; that is, individual ganglion cells respond to both rod and cone inputs, depending on the level of illumination. The early stages of the pathways that link rods and cones

to ganglion cells, however, are largely independent. For example, the pathway from rods to ganglion cells involves a distinct class of bipolar cells called rod bipolar that, unlike cone bipolar cells, does not contact retinal ganglion cells. Instead, rod bipolar cells synapse with the dendritic processes of a specific class of amacrine cells that makes gap junctions and chemical synapses with the terminals of cone bipolars. These processes, in turn, make synaptic contacts on the dendrites of ganglion cells in the inner surface layer.

Moreover, the rod and cone systems differ dramatically in their degree of convergence; a factor which contributes greatly to their distinct properties. Each rod bipolar cell is contracted by a number of rods, and many rod bipolar cells contract a given amacrine cell. In contrast, the cone system is much less convergent. Thus, each retinal ganglion cell that dominates central vision (called midget ganglion cells) receives input from only one cone bipolar cell, which in turn is contacted by a single cone. Convergence makes the rod system a better detector of light, because small signals from many rods are pooled to generate a large response in the bipolar cell. At the same time, convergence reduces the spatial resolution of the rod system; since the source of a signal in a rod bipolar cell or retinal ganglion cell could have come from anywhere within a relatively large area of the retinal surface. The one-to-one relationship of cones to bipolar and ganglion cells is, of course, required to maximize acuity.

Mechanism of photoreception

Rods contain light sensitive pigment rhodopsin, which is attached to the outer surface of vesicles. Rhodopsin is a molecule formed by the combination of a protein called scotopsin with a small light-absorbing molecule called retinene which is a carotenoid molecule derived from vitamin A. When the rhodopsin molecule is exposed to bright light, it breaks down into retinene and scotopsin. This process is called bleaching.

$$\text{Rhodopsin} \xrightarrow{\text{Bleaching}} \text{Retinene} + \text{Scotopsin}$$

Rhodopsin is reformed immediately when light stimulation decreases. Trans retinene is first converted into cis retinene and then recombined with scotopsin. This process is called dark adaptation. Similary, the cone system has a very high spatial resolution but it is relatively insensitive to light. It is therefore specialised for acuity at the expense of sensitivity. This property of the cone system allows us to see colour.

Physiology of seeing

The eye works on the same principle as that of the camera. Light rays from the object pass from the external part of the eye to the retina through the conjunctiva, cornea, aqueous humour and pupil (Figure 4.30). The pupil is an opening (an aperture) which is controlled by the iris (like camera shutters) depending on the amount of light. The stronger the amount of light, the smaller the size of the aperture. The lens is positioned between the outer and inner chambers of the eye, and its major function is to focus images on the retina by changing its thickness

depending on the amount of light from distant or nearby objects. On the retina, there are cone and rod photoreceptors, which are connected to the brain via a bundle of fibres called optic nerve. The information received is processed in the brain, and consequently, the object can be seen. Thus, the role of the retina is to translate light into nerve signals and allow us to see under various conditions ranging from starlight to sunlight. It also distinguishes the wavelengths for us to discriminate colors.

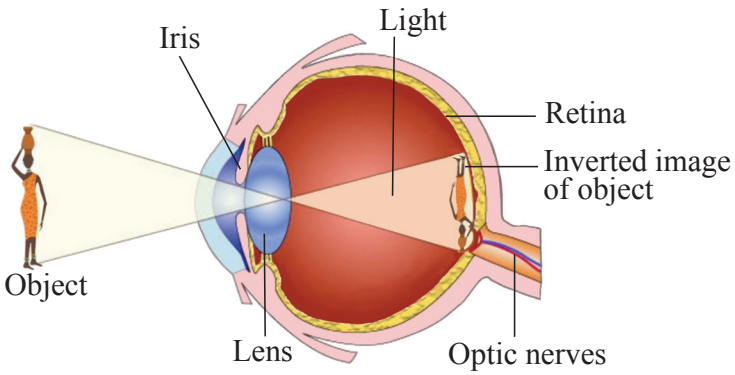


Figure 4.30: Structure of a mammalian eye showing physiology of seeing

The mammalian ear

The mammalian ear consists of three parts, namely the outer, middle and inner ear. The outer ear comprises of an external flap of skin covered by elastic cartilage called pinna. The pinna collects sound waves and directs them into the ear canal (external auditory meatus). Across the end of ear canal is a tympanic membrane or ear drum which separates the outer ear from the middle ear. The opening of the auditory canal is lined with fine hairs and glands which secrete earwax, which is located in the upper wall of the auditory canal. Ear wax guards the ear against entrance of foreign materials such as dust and microorganisms.

In the middle ear, the tympanic membrane begins and ends at a bony wall containing two small openings covered by membranes. The two openings are oval window (fenestra ovalis) and the round window (fenestra rotunda). There are three connected bones called ear ossicles, which are held in position by muscles. These are malleus (hammer), incus (anvil), and stapes (stirrup). The middle ear is air filled part that depends on the equalization of pressure outside and inside the ear to prevent damaging the ear drum. There is a eustachian tube (auditory tube) which connects the middle ear to the pharynx. Via this tube, air enters and leaves the middle ear during swallowing to equalise pressure (Figure 4.31).

Unlike the outer ear and middle ear which is filled with air, the inner ear comprises of a complex system of fluidfilled tubes. The cochlea, the coiled structure, is an organ for hearing while the semicircular canal and the vestibule are organs for body balance.

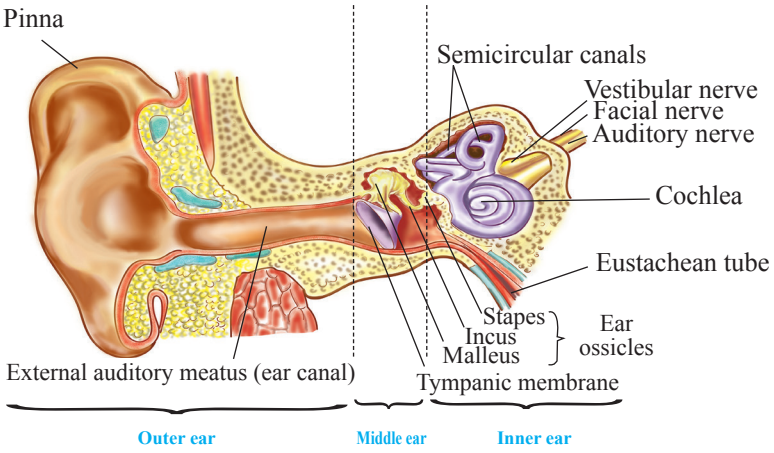


Figure 4.31 Structure of a mammalian ear

The structure of the membranous labyrinth of the mammalian inner ear

There are two labyrinths in the inner ear, namely the bony labyrinth and membranous labyrinth; one is inside the other. The membraneous labyrinth is comprised of the cochlea, vestibule and three semicircular canals. All these structures contain a fluid called perilymph. Membranous labyrinth lies within the bony labyrinth.

The membranous labyrinth is a continuous system of ducts filled with endolymph. It is comprised of the cochlear duct, three semicircular ducts, saccule and the utricle. The cochlear duct is situated within the cochlea and is the organ of hearing. The semicircular ducts, saccule, and utricle are the organs for balance, are also known as the vestibular apparatus. The cochlear duct is located within the bony scaffolding the cochlea. It is held in place by the spiral lamina. The saccule and utricle are two membranous sacs located in the vestibule.

The utricle is larger than saccule, and it receives the three semicircular ducts. The saccule is globular in shape and receives the cochlear duct. Endolymph drains from the saccule and utricle into the endolymphatic duct. The duct extends through the vestibular aqueduct to the posterior aspect of the petrous part of the temporal bone. Here, the duct expands to a sac where endolymph can be secreted and absorbed. Semicircular ducts are located within the semicircular canals, and share their orientation (Figure 4.32).

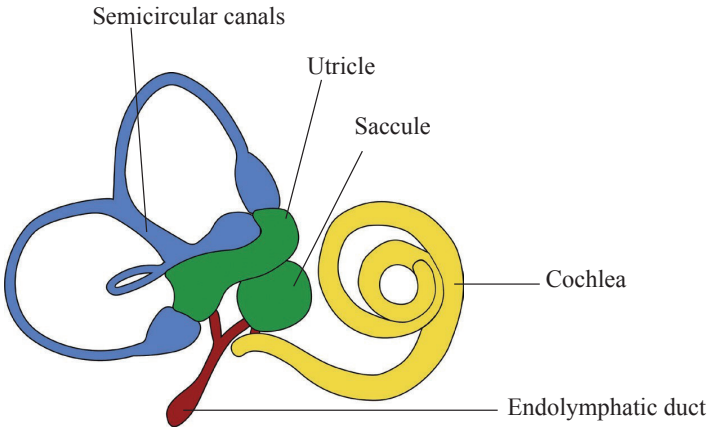


Figure 4.32 Components of the membranous labyrinth

Mechanism of hearing

The mammalian ear functions as an organ for hearing and balance. The process of hearing starts when sound waves enter the outer ear and travel through the external auditory canal until they reach the tympanic membrane, causing the membrane and the attached chain of auditory ossicles to vibrate. The malleus then takes the pressure from the inner surface of the tympanic membrane and passes it by means of the incus to the stapes. There are about 20 times multiplication of sound pressure as it moves from outside to inner ear.

The motion of the stapes against the oval window sets up waves in the fluids of the cochlea, causing the basilar membrane to vibrate. This stimulates the sensory hair cells of the organ of corti, on the basilar membrane, to send nerve impulses to the brain. When they reach the auditory area of the cerebral cortex, they are interpreted as a sound. Many sensory hair cells with different thresholds at which they are stimulated exist. The louder the sound, the greater the number of sensory hair cells will be stimulated at any one point of the basilar membrane (Figure 4.33).

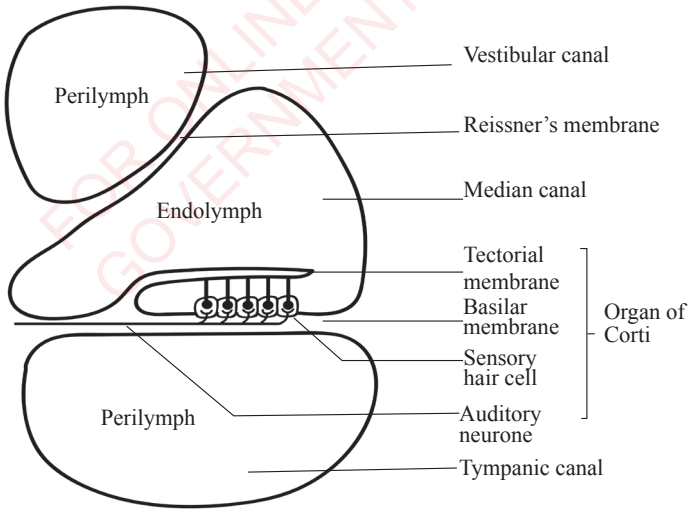


Figure 4.33 Transverse section of cochlea showing the organ of corti

Maintaining body balance in mammals

The parts of the ear which are concerned with balance are the semicircular canals and vestibule. The semi circular canals are three curved tubes containing endolymph, which communicates with the middle chamber of the cochlea via the utriculus and sacculus. Each of the three canals is set in a plane at right angles to the other. Any movement in any plane will cause movement of canals in the direction of the head. Each of the three canals possesses a swollen portion, the ampulla, within which there is a flat gelatinous plate, the cupula. The movement of endolymph displaces the cupula in the opposite direction to the head movement. The sensory hair found at the base of the cupula detects the displacement and sends impulse to the brain through the vestibular nerve. The brain then initiates motor impulses to various muscles to correct the imbalance (Figure 4.34).

All information that aid balance and positioning of the body relative to gravity, as well as changes in the position due to acceleration and deceleration is provided by utriculus and sacculus. Such information is provided by granules known as otoliths which are embedded in jellylike materials. Various movements of the head cause this otolith to displace sensory hair cells on the regions of the walls of utriculus and sacculus which respond to vertical and lateral movements respectively. Then the sensory hair cells send appropriate sensory impulse to the brain.

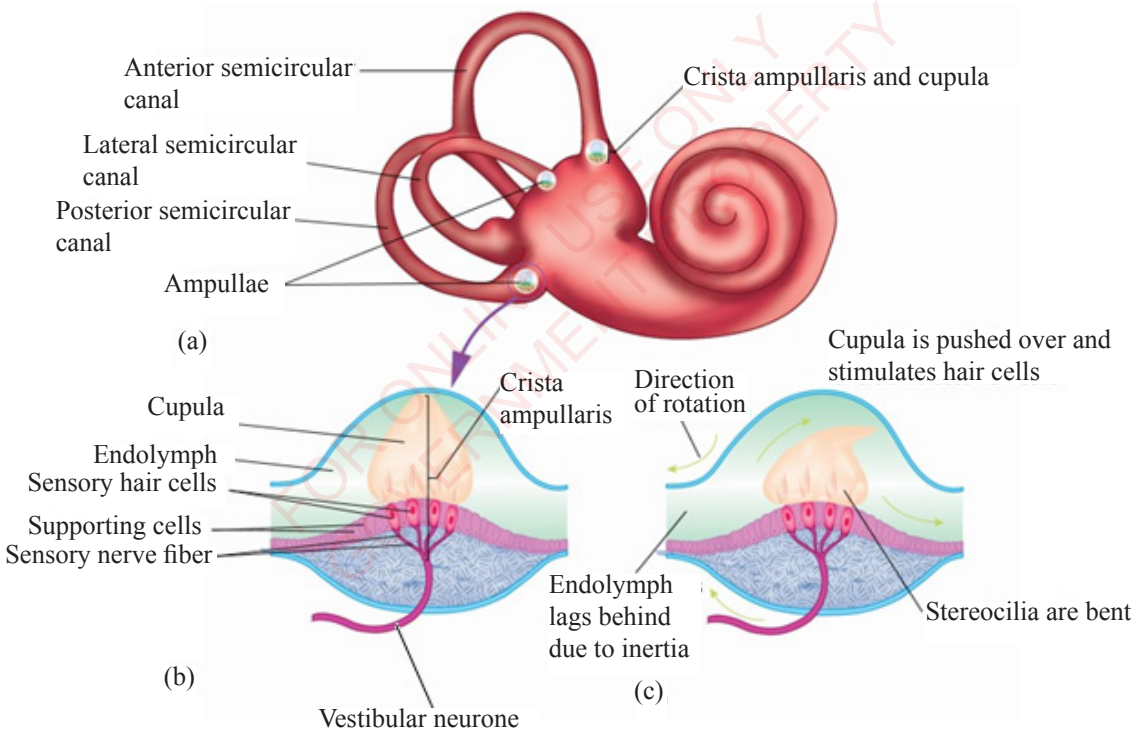


Figure 4.34 Structure of the semicircular canals showing (a) position of ampula and cupula (b) section of ampula at stationary and (c) section of ampula during body movement

Activity 4.1
Stand upright and rotate your body several rounds (about 5 times). Stop and explain with reasons how you feel.

Exercise 4.3

1. Name the main types of sensory receptors and explain their functions in the mammalian body.
2. Explain the process of accommodation in mammalian eye.
3. Describe the structure of retina.
4. Describe the structure of the membranous labyrinth of the mammalian ear.
5. Explain the mechanism of hearing in mammals.
6. Explain how semicircular canals function with respect to balance and posture in mammals.

4.3 Hormonal coordination in mammals

Hormonal coordination in mammals is a function of the endocrine system, which is composed of a series of glands known as endocrine glands. They are called endocrine glands because they are ductless. The system is called "endocrine" to distinguish it from "exocrine" glands that use ducts to convey their chemical agents to the target cells or substances e.g. glands producing digestive enzymes. These glands secrete specific chemical fluids called hormones directly into the blood stream. Due to this reason, the endocrine gland is surrounded by numerous blood vessels. A hormone is a chemical messenger produced by a ductless gland, transported by blood and shows its effects in a region away from the site of production. Table 4.2 gives a list of some hormones, endocrine glands and where they are produced (Figure 4.35), and the activity that they regulate.

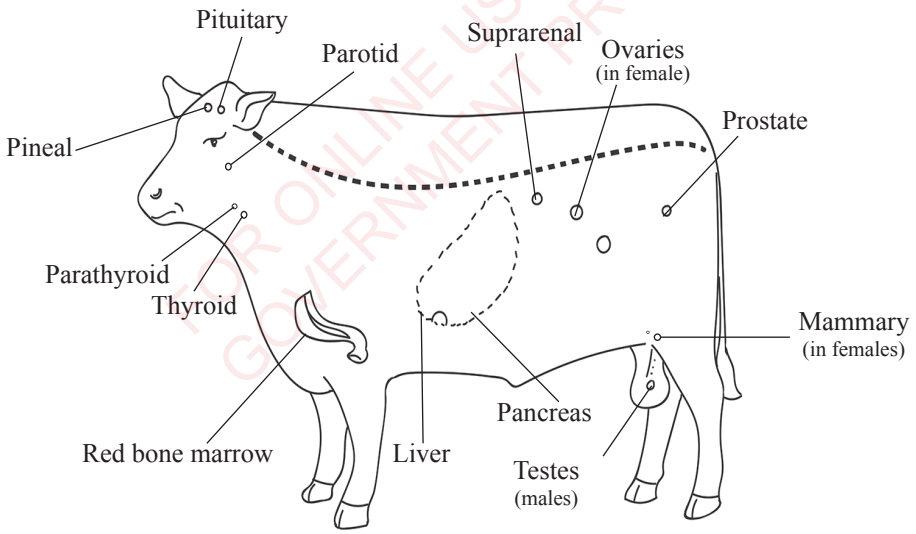


Figure 4.35 Location of endocrine glands in a cow

Table 4.2 Hormones, glands where they are produced and the activity they regulate

Endocrine gland	Hormone(s) produced	Functions
Thyroid	Thyroxine, Triiodothyronine	Regulate vital body functions. Stimulates and maintains metabolism, growth and development.
	Calcitonin	Reduction of blood Ca_2^+ levels.
Parathyroid	Parathyroid Hormone (PTH)	Control calcium within the blood.
Adrenal (Cortex)	Aldosterone	Increases blood Na^+ levels; increase K^+ secretion.
	Cortisol, Corticosterone, Cortisone	Regulates blood pressure. Increases blood glucose levels; anti-inflammatory effects.
Adrenal (Medulla)	Epinephrine (Adrenaline) Norepinephrine	Stimulates fight-or-flight response, increases blood glucose levels and increase metabolic activities.
Pancreas	Insulin	Reduces blood glucose levels.
	Glucagon	Increases blood glucose levels.
Pineal gland	Melatonin	Regulates some biological rhythms and protect CNS from free radicals.
Testes	Androgens	Regulates, promotes, increases or maintains sperm production and male secondary sexual characteristics.
Ovaries	Oestrogen	Promotes uterine lining growth and female secondary sexual characteristics.

Properties of hormones

Hormones are all produced by specific cells of endocrine system, they are transported through the blood, they show their effect to the site away from its source, hormones are specific for a particular target, they are soluble organic molecules and are effective even at low concentration.

Feedback mechanisms for hormonal coordination

The release of hormones by glands is controlled by several factors, including the presence of specific metabolites in the blood. For example, excess glucose in the blood triggers the pancreas to release insulin to lower the level of blood glucose. Another factor is the presence of another hormone in the blood. Majority of the hormones released from the anterior pituitary gland are stimulating hormones, which direct other glands to secrete their hormones. For instance, the growth hormone releasing factor causes the release of the thyroxin hormone. Stimulation by neurones from the autonomic nervous system can also cause secretion of hormones. Under the condition of stress, fear or danger, the body secretes hormones to combat the situation.

The timing of hormone release and the amount of hormone to be released are regulated by a feedback mechanism. Feedback mechanisms are self regulatory mechanisms in which when there is a disturbance or deviation in a system, series of events occur to either remove the disturbance (negative feedback) or make the system to deviate further (positive feedback). Usually, it is a negative feedback mechanism which regulates the release of hormones. In rare cases positive feedback mechanisms may occur. An example of the negative feedback mechanism is the release of the thyroxine hormone (Figure 4.36).

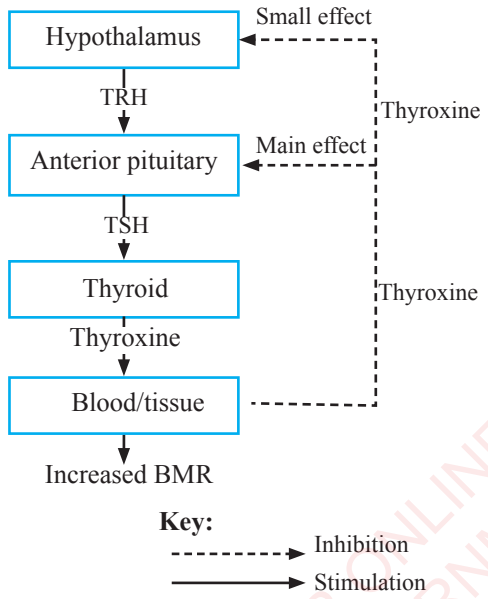


Figure 4. 36 Factors regulating thyroxine secretion and homeostatic control of the metabolic rate

Thyroxine helps in regulating the metabolic rate, growth and development of an organism. The control of the release of thyroxine is determined by the level of thyroxine with four iodine atoms (T4) circulating in the blood. If there is high concentration of T4 in the blood, it inhibits further production by inhibiting the production of Thyrotropin Releasing Hormone (TRH) by the hypothalamus and thyroid stimulating hormone (TSH) by anterior pituitary gland. Therefore, in this case, the product of a series of reactions controls its own production by turning off the pathway, when it reaches a certain level.

Negative feedback is also observed in production and regulation of insulin in the body. A rise of sugar level in the blood is detected by β cells of islets of Langerhans of the pancreas, which release the insulin hormone. The hormone will then convert glucose into glycogen which is stored in the liver and muscles. This causes the level of sugar in the blood to decrease. The lower level of glucose then causes the β cells to reduce production of insulin. This, inturn, triggers the release of glucagon from α-cells of islets of Langerhans of the pancreas. This hormone converts glycogen into glucose.

The interaction between hormonal and nervous systems

Coordination process is achieved when nervous and endocrine systems act together. Although the nervous system and the endocrine system are two different systems, both release chemical substances as a means of communication between cells. The principal role of both systems is to coordinate and control various physiological activities in organisms. The major centres for linking the two systems are the pituitary gland (control centre for endocrine glands) and the hypothalamus (the control centre for the nervous system). The hypothalamus collects information from the brain and blood vessels passing

through it to the pituitary gland. The pituitary gland directly or indirectly controls the secretions of other endocrine glands.

The pituitary gland, which is located at the base of the brain, is directly connected to the brain region called hypothalamus. This physical link between the hypothalamus and pituitary is the basis for the connection or link between the central nervous system and the endocrine system. The pituitary has two distinct segments, namely the anterior pituitary and the posterior pituitary. The anterior pituitary gland is connected by blood vessels called the portal system, which has one capillary bed in the hypothalamus and another in the anterior pituitary. Also it has nerve terminals that release two groups of chemical substances known as releasing and inhibiting factors into the blood capillaries at the hypothalamus end of portal system. These chemical substances pass to the pituitary end and cause the release of six trophic hormones (hormones that stimulate other endocrine hormones to release hormones) which are stored in the anterior pituitary gland.

In the year 1930, a biologist documented the consequences of removing the entire pituitary from laboratory rats. As a result of pituitary removal, the animals stopped growing, failed to maintain normal body temperature, and suffered atrophy (shrinkage) of their genitals, thyroid glands, and adrenal cortex. Not surprisingly, their life span shortened dramatically. These experiments suggested that, in addition to secreting growth hormones, the pituitary secretes hormones that regulate the production of a wide variety of other hormones. All pituitary hormones stimulate the release of target gland hormones. As their levels increase, they inhibit the secretion of hypothalamus and pituitary hormones. When their levels in the blood fall below a certain level, hypothalamus and pituitary inhibition stop and start secreting their chemicals again. This is also referred to as a negative feedback mechanism.

The posterior pituitary gland is an extension of the brain. It stores and releases antidiuretic hormone (ADH) or vasopressin and oxytocin hormone which are produced by neurosecretory cell bodies, lying in the hypothalamus. They pass down the nerve fibres. Nerve impulses are relayed to the cell bodies of these neurosecretory cells from other regions of the brain. They are transmitted down the axons, where hormones are stored in vesicles (Figure 4.37). The whole process involves both nervous and endocrine systems. This is referred to as a neuroendocrine response, resulting into a pattern of behaviour known as a neuroendocrine reflex.

ADH is released in response to a fall in the water content of blood plasma and leads to an increase in the permeability to water of distal convoluted tubule in the nephron of the kidney. On the other hand, oxytocin causes the contraction of the uterus during birth and ejection of milk from nipples. Oxytocin and contraction of the uterus is a positive feedback mechanism. The more the concentrations of oxytocin, the stronger the contraction of the uterus becomes.

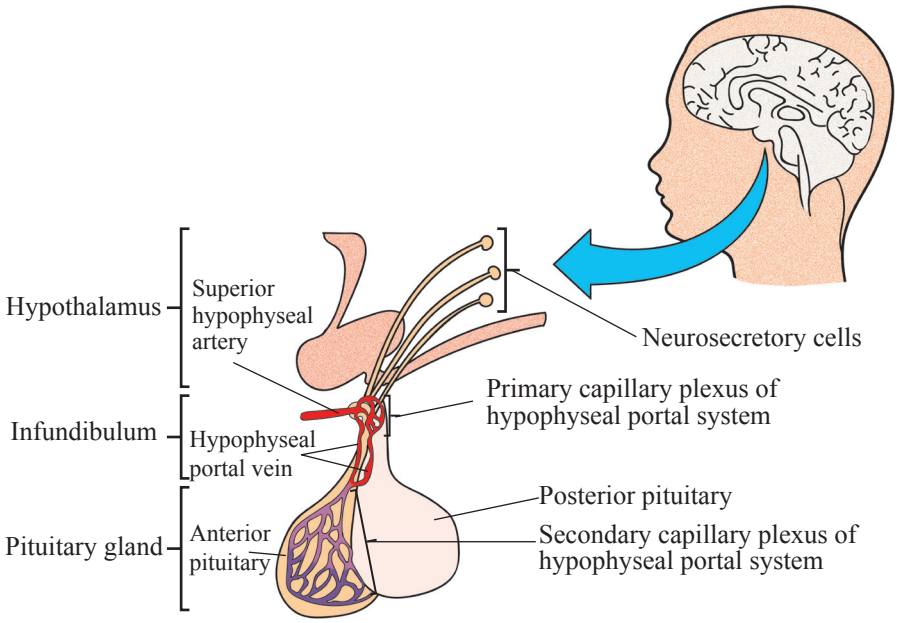


Figure 4.37 Relationship between the hypothalamus and pituitary gland

Exercise 4.4

1. Explain the feedback mechanisms of hormonal coordination.
2. Describe the interaction between hormonal and nervous systems in the mammalian body.
3. The pituitary gland is said to be a master gland. Substantiate.
4. Explain the role of hypothalamus in coordination.

4.4 Coordination in plants

Plants do not have a nervous system; they rely on chemical coordination. Therefore, most of their responses are slower compared to animals. Unlike animals, plants do not move from one place to another; although the movement is shown by the characteristics of plants' sensitivity and response to external stimuli which results into growth movements and also movement of organs. There are three types of growth movements in plants, namely tactic movement, nastic movement, and tropic movement.

a) Tactic movement

Tactic movement; also known as taxis (plural taxes) is the type of movement which involves the entire cell or organism moving from one place to another in response to external stimuli such as light, water, and chemicals. Tactic movement occurs in plant reproductive cells and in some organisms such as *Euglena,* and *Chlamydomonas*. Taxes may be grouped as positive taxis and negative taxis. A positive taxis is when an organism or cell moves towards the source of stimulation, while negative taxis is when an organism or cell moves away from

the source of stimulation. For example, *Chlamydomonas* always moves towards light of low intensity and away from light of high intensity. This type of response is known as phototactic response or phototaxis. In this example, the movement towards light of low intensity is a positive phototaxis, whereas, that away from light of high intensity is a negative phototaxis.

Types of tactic movements (taxes)

Based on the nature or kind of a stimulus involved, different types of tactic movements (taxes) can be identified. Examples of taxes include phototaxis (response to light) which can be seen in *Euglena* and blue green algae and chemotaxis (response to chemicals) as seen in lower plants such as *Funaria* where by male gamete move towards the chemical substance released by egg cells. Others include geotaxis (gravity), aerotaxis (oxygen), magneotaxis (magnetic field) and rheotaxis (water current).

b) Nastic movement

Nastic movement is a non-directional movement of a part of stationary plant in response to an external stimulus. Based on the nature of stimuli, nastic movements can be divided into the following groups:

Nyctinasty

This is a nastic movement which occurs in response to diurnal changes of temperature (thermonasty) or light intensity (photonasty). An example of nyctinasty is the opening and closing of petals of some flowers that occur in response to alternation in the duration of day and night. Another example is sleep movements of leaves of some leguminous plants in response to the onset of darkness.

Thermonasty

This is a movement of plant parts in response to temperature. For example, some flowers close when the temperature drops, or some leaves fold when the temperature is too high.

Chemonasty

This is the movement of plant parts in response to chemicals stimuli, for example, sundew plants close glandular hairs due to chemical produced by insect when land on it, this prevents escape of the insect.

Photonasty

This is the movement of plant parts in response to light. For instance, some flowers or leaves fold following the sun shine, or the opening and closing of flowers depending on whether it is day or night (Figure 4.38).

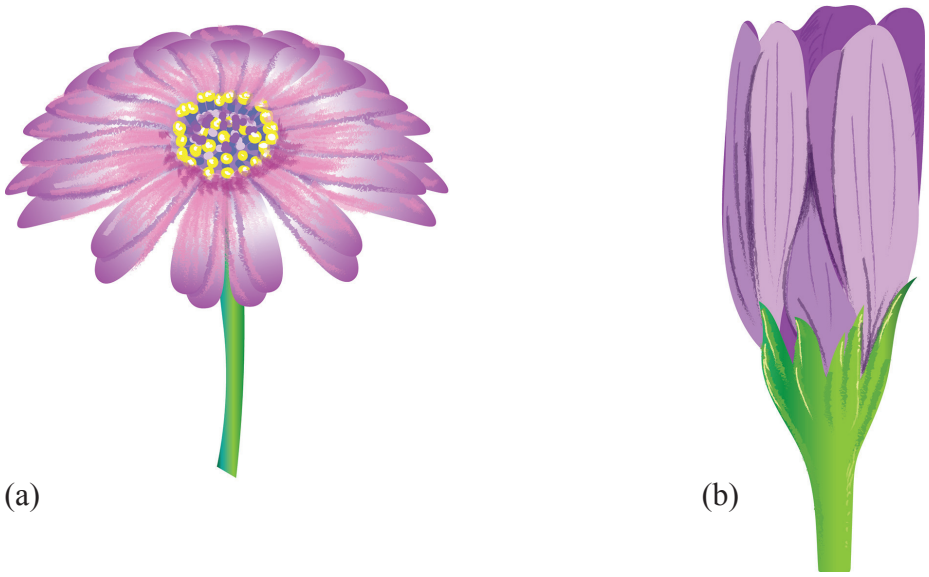


Figure 4.38 Nastic movement in flower (a) during the day the flower opens and (b) during the night the flower closes

Seismonasty

This is the movement of plant parts in response to touch. Seismonastic movement is also known as thigmonastic movement. An example of seismonastic movement is folding of leaves of *Mimosa pudica* in response to touch (Figure 4.39).

Generally, nastic movement can result from changes in turgor or growth rate between different sides of the plant part. For example, changes in the water contents of the tissues at the base of the leaf of the *Mimosa* plant results in the shrinkage and folding of its leaflets. Such response may be due to different stimuli, such as light, touch, heat, or electric shock. After a suitable recovery period, the leaflets open again. Normally, they remain expanded during the day while closed at night.

Figure 4.39 Nastic movement in the leaflets of the *Mimosa* plant

c) Tropic movement

This is the movement of part of a plant associated with growth of plant tissue caused by a differential concentration of plant hormones, usually auxins, under a specific stimulus. The stimuli involved include light, gravity, water/humidity, and pressure or touch, among others. Some common examples of tropic movement in plants include phototropism, geotropism, and hydrotropism.

Phototropism. Plant growth movement associated with light. Shoots tend to grow towards light (positive phototropic movement), and if the light is coming from a single direction the plant will bend towards that source of light (Figure 4.40). The roots show the opposite tendency (negative phototropism).

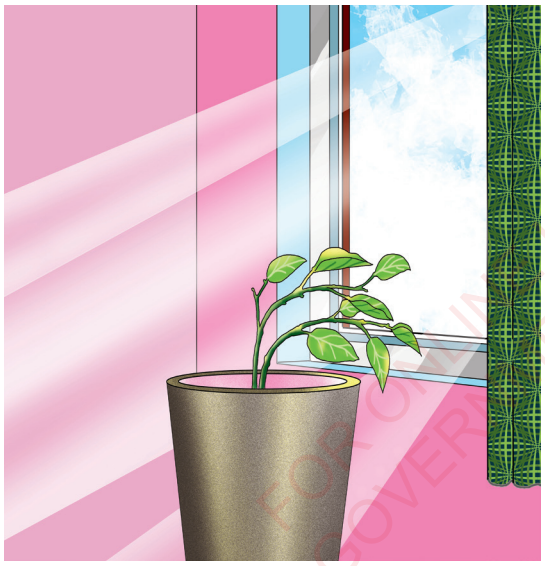


Figure 4.40 Shoot grow towards light

Geotropism. This is caused by the earth's gravitational pull. Shoots show negative geotropic movement, that is, they grow away from the force of gravity, while roots show positive geotropism. If a potted plant is kept in a horizontal position, the shoot will bend and start growing in an upright direction while the roots change their direction of growth downwards (Figure 4.41).

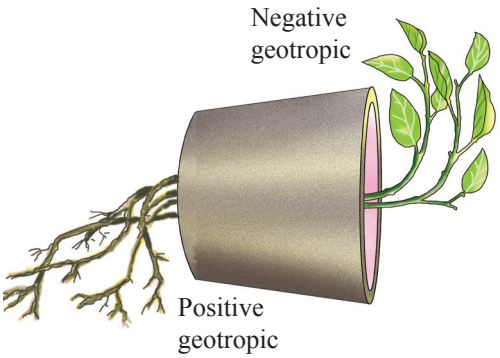


Figure 4.41 Geotropism in plant

Hydrotropism. Hydrotropism takes place in response to moisture. Roots are generally positively hydrotropic (Figure 4.42 a and b).

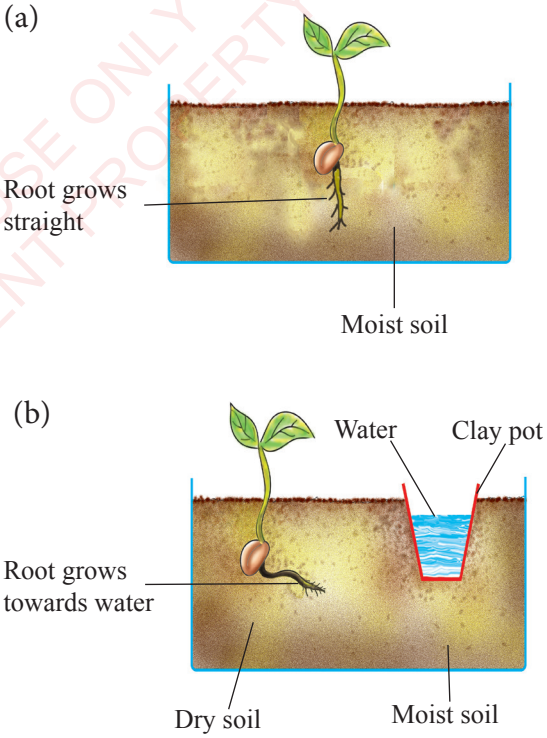


Figure 4.42 Movement of roots towards water (a and b)

Exercise 4.5

1. Distinguish between plant and animal coordination.
2. Explain the following terms:
   a) Tactic movement
   b) Nastic movement
3. With examples, differentiate between seismonasty and photonasty.

4.5 Plant hormones (Phytohormones)

Plant hormones or plant growth hormones are chemical substances that regulate plant growth. They are also known as phytohormones or plant growth regulators. Plant hormones are signal molecules produced within the plants and usually occur in extremely low concentrations. They regulate cellular processes in targeted cells within the plant.

Characteristics of plant hormones

a) Plant hormones are chemicals that are required in small amounts to promote and influence growth, development and differentiation of plant cells and tissues. They are active and effective even at very low concentrations.

b) They are produced in certain parts of the plant and transported to other parts of the plant where they elicit specific biochemical, physiological or morphological responses.

c) They are transported within the plants by four different types of movements namely; localised movement, cytoplasmic streaming, slow diffusion of ions, and through vascular tissues (xylem and phloem).

d) Each plant hormone evokes many different responses.

e) The effects of different plant hormones overlap and may be stimulatory or inhibitory.

f) Each plant hormone performs specific functions in the plant body.

g) The biosynthesis of plant hormones within plant tissues is always diffuse, not localized.

h) The production of plant hormones occurs very often at sites of active growth within meristems, before cells have been fully differentiated. After the production, they are sometimes moved to other parts of the plant, where they cause an immediate effect; or they can be stored in cells to be released later.

Types of plant hormones

There are five main types or groups of plant hormones. These are auxins, gibberellins, cytokinins, ethene (ethylene), and abscisic acid (ABA). These hormones can perform their functions either independently or synergistically (working together to effect a certain function). For example, auxins are known as growth promoters, since they influence plant growth and assist in producing a phototropic response which results into growth. Sometimes, auxins and gibberellins act together to bring about cell elongation. This is called synergism. Alternatively, two plant hormones may work opposing one another, like auxins which induces apical dominance while cytokinins prevent it. This is known as antagonism.

Auxins

Auxins are chemical compounds produced in the root and shoot apices of the plants. One of their common forms is Indoleacetic Acid (IAA). Auxins have the following role in plants:

a) They influence cell enlargement, bud formation, and root initiation.

b) They facilitate production of phototropic response.

c) Auxins together with cytokinins control the growth of stems, roots, and fruits.

d) They affect cell elongation by altering cell wall plasticity.

e) They stimulate cambium of meristematic cells to develop stems, leaves and flower buds, while in stems, they differentiate secondary xylem.

f) They inhibit the growth of lateral buds, hence promote apical dominance.

g) They promote lateral and adventitious root development and growth.

h) They regulate specific protein synthesis in seeds as they develop within the flower after pollination.

i) They stimulate development of fruits without fertilisation (parthenocarpy).

j) They inhibit abscission in leaves and fruits.

Application of synthetic auxins in crop production

Auxins can be synthesised for agricultural use. It is a proven fact that synthetic auxins are more useful and cheaper than naturally produced auxins. Synthetic auxins play the following roles in agriculture:

a) Promote fruit setting

The synthetic auxins such as Indolebutyric acid (IBA) and Naphthalene acetic acid (NAA) are used to promote fruit setting. Fruit setting involves a series of changes taking place after fertilisation in the ovary, resulting into development of a fruit. Auxins can be used for setting some fruits such as tomatoes and pepper, resulting into production of fruits without fertilisation. NAA can also be used to control pre-harvest fruit drop and fruit thinning in various crops such as apples.

b) Promote rooting in cuttings

Auxins (IBA and NAA) are very effective in stimulating root development from stem cuttings. This is commonly applied in crops that are propagated through stem cutting, such as cassava. This form of asexual reproduction ensures that no change can occur in the genetic make up of the plants.

c) Weed killers

Phenoxyacetic acid is used as a selective weed killer as it kills broad leaf plant species, especially dicotyledons; hence it is used in removing dicotyledonous weeds in cereal (monocotyledonus) crops. Benzoic acids are also used as a powerful weed killer, thus they are used against deep-rooted weeds.

d) Prevent sprouting in potatoes

Phenoxyacetic acid is used to prevent sprouting in potatoes. It is also used to prevent premature falling of fruits and leaves in crop plants.

Gibberellins

Gibberellins such as Gibberellic Acid (GA) include a wide range of chemicals that are produced naturally within plants. Like auxins which can be produced in industry, gibberellins are also commercially produced from fungal culture. They perform the following role in plants:

a) They stimulate stem elongation and pollen tube growth.

b) Influence cell division.

c) They promote flowering, seed germination and differentiation after germination.

d) They are important in seed germination, as they effect enzyme production that mobilises food production needed for growing new cells. This is done by modulating chromosomal transcription in the growing seedling.

e) Promote bolting in rosette plants, hence increasing inter nodal lengths.

f) Promote cell division and elongation in the presence of auxins.

g) Reverse the inhibition of shoot growth and dormancy induced by Abscisic acid.

h) Break seed dormancy.

Application of synthetic gibberellins in crop production

The synthetic gibberellins have the following role in plants:

a) They promote fruit setting.

b) They enhance malting in brewing industries.

c) They reverse genetic dwarfism.

d) They break seed dormancy.

e) They increase plants' resistance to pests and diseases.

Cytokinins

Cytokinins (CKs) are a group of chemicals that influence cell division and shoot formation in plants. In the past, when the cytokinins were first isolated from yeast cells they were called 'kinins'. They are found mostly in regions of rapid cell division, particularly in seeds and fruits, where embryos develop. They perform the following role in plants:

a) They promote cell division in the presence of auxins.

b) They induce delayed senescence of leaves and fruits.

c) They are responsible for mediating transportation of auxins throughout the plant and affecting internodal length and growth.

d) They promote lateral bud growth.

e) They counter the apical dominance induced by auxins.

f) They break seed and bud dormancy at appropriate temperatures.

Application of synthetic cytokinins in crop production

Synthetic cytokinins have the following application in crop production:

a) They are used to prolong the shelf life of fresh crops such as cabbage and lettuce.

b) They break bud and seed dormancy.

c) They keep flowers fresh.

Ethene (Ethylene)

Unlike other plant hormones, ethene is in gaseous state. It is formed from the amino acid methionine and released from ripening fruits, nodes of stems, ageing leaves, and flowers. It is produced as a metabolic byproduct of most plant organs. It plays the following role in plants:

a) It stimulates ripening of fruits.

b) It is involved in axillary bud inhibition. This occurs when auxins are transported from the apical meristem of the stem downward, stimulating the production of ethylene, which suppresses axillary bud development.

c) It suppresses stem and root elongation, especially during physiological stress as in drought.

d) It breaks bud dormancy.

Application of synthetic ethylene in crop production

Synthetic ethylene has the following application in agriculture:

a) It promotes fruit ripening within a relatively short period of time.

b) It is applied to citrus fruits to attain attracting colours before being presented for sale.

c) It induces flowering in pineapples.

d) It stimulates the latex flow in rubber trees.

Abscisic Acid (ABA)

ABA is also known as stress hormone; because its production is stimulated by environmental stress or other adverse conditions, such as drought and water logging. In contrast to other growth substances such as auxins, gibberellins, and cytokinins, which are plant growth promoters, ABA is a growth inhibitor; hence it acts antagonistically to the growth promoters. It is produced by any tissue containing chloroplasts. It is concentrated in leaves, fruits, and seeds. The term abscisic acid originates from the belief that it was a direct cause of leaf fall (abscission), although this is now known to be not true. Abscisic acid has the following role in plants:

a) It promotes dormancy and inhibits growth.

b) It causes abscission (fall of leaves and fruits). When fruit ripens, the level of auxins which inhibits abscission falls, while that of abscisic acid which promotes abscission increases.

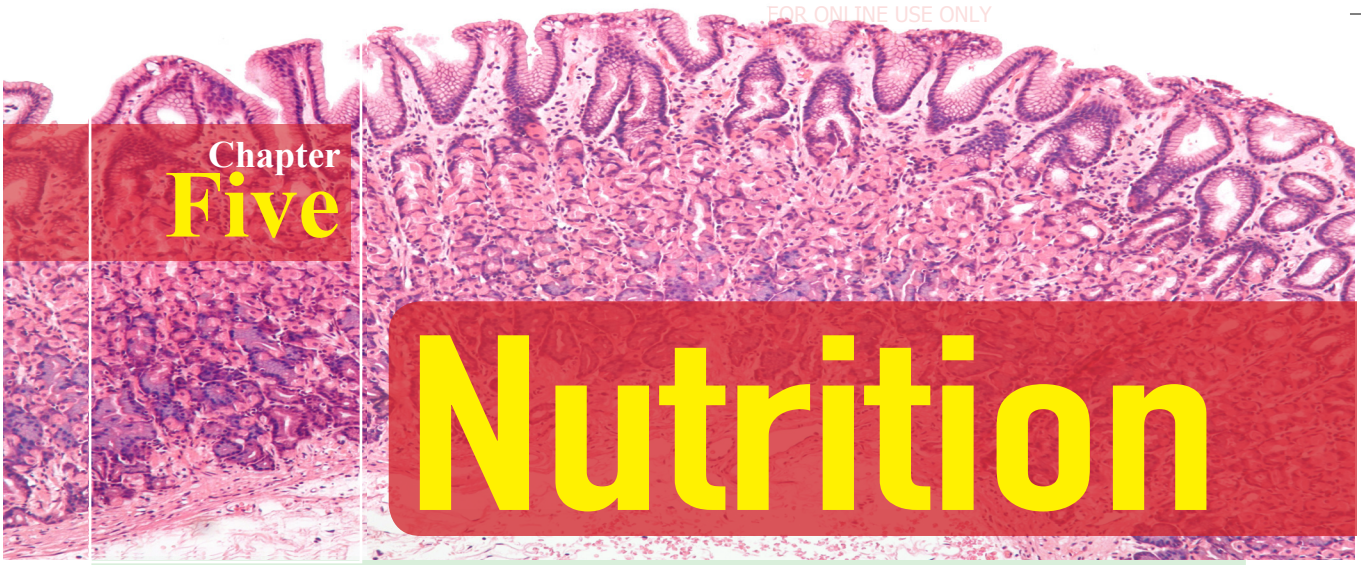
c) It promotes closing of stomata under water stress conditions.

Application of synthetic abscisic acid in crop production

Abscisic acid can be sprayed on tree crops to regulate fruit fall at the end of the season. This helps to ensure that fruits fall at the time; hence avoiding the need for repeating picking of fruits over a long time span.

Revision questions

1. State the functions of cell body and myelin sheath.
2. Describe the characteristics of a nerve impulse.
3. Explain how an impulse is transmitted across the synapse.
4. Draw a well labelled diagram of the mammalian ear.
5. What are the major differences between the nervous system and hormonal system?
6. Outline the differences between rods and cones.
7. Describe types of tactic movements.
8. Explain the concept of nastic movement.
9. Outline the role of phytohormones in plants.
10. Explain the application of natural and synthetic phytohormones in crop production and weed control.
11. Explain the role of synthetic phytohormones for the development of industrialised Tanzania.



Chapter
Five

Nutrition

Introduction

Living organisms require energy in order to accomplish various metabolic activities. The main source of energy for organisms in all ecosystems is the sun. Organisms obtain their food in different ways. Autotrophs use light energy and simple inorganic substances such as water and carbon dioxide from their environment to synthesize their own food. Heterotrophs, on the other hand, obtain already made complex organic molecules such as carbohydrates, proteins and fats, break them down, assimilate and use them to maintain their life functions. In this chapter, you will learn about food manufacturing in plants and digestion in mammals.

5.1 Concept of nutrition

There are different modes of nutrition by which living organisms obtain food in order to obtain energy and nutrients that are required for different metabolic activities and survival. Nutrition entails a process by which living organisms take in food and use it for metabolic activities such as growth, and body repair. Based on their modes of nutrition, living organisms are categorised into two main groups namely; autotrophs and heterotrophs. All organisms that can make their own food from simple inorganic substances such as water and carbon dioxide are called autotrophs. Autotrophs such as plants, green algae, and some bacteria, have the green pigment (chlorophyll) used to synthesize food. This is the process known as photosynthesis. A second group of autotrophs use a process known as chemosynthesis. Sulphur bacteria, for example, use inorganic sulphur as the source of energy for synthesizing their food, and *Methanobacter* sp. (bacteria living in deep oxygen-depleted oceans) use methane as a source of energy. Other organisms that cannot make their own food but depend on other organisms for food and energy are called heterotrophs. These include animals, fungi and some bacteria.

5.2 Autotrophic nutrition

In this type of nutrition, organisms acquire energy from sunlight and utilize it to

synthesize their food using carbon dioxide (CO_2) obtained from the atmosphere. The organisms that are capable of utilizing sunlight or chemical energy to make their own food from simple inorganic materials are referred to as autotrophs, which literally mean self-feeders. Autotrophs such as plants, cyanobacteria, algae, purple sulphur bacteria, purple non-sulphur bacteria, and green sulphur bacteria use sunlight energy and chemial energy to manufacture their food. These are collectively called photoautotrophs, which is a combination of three Greek words: *photos, auto,* and *trophos* meaning 'light,' 'self,' and 'nourishment or feeders' respectively. Therefore the term photoautotroph literally refers to an organism capable of manufacturing its own food using light energy. Photoautotrophs such as plants, cyanobacteria and algae contain green pigments such as chlorophyll *'a', 'b'* and 'carotenoid'. These pigments are important in absorbing light energy which is vital in the synthesis of food in plants by the process known as photosynthesis. Bacteria contain bacteriochlorophyll which performs the same function as chlorophyll. Generally, the light absorbed by the chlorophyll in green plants is converted into chemical energy during photosynthesis.

Besides light, inorganic chemicals are the alternative sources of energy for the synthesis of food. Energy from such chemicals is normally acquired by these organisms through oxidation reactions. For example, Iron bacteria called *Ferrobacillus* obtain their energy by oxidising ferrous to ferric ion, sulphur bacteria called *Thiobacillus thiooxidans* (also known as *Acidithiobacillus thiooxidans*) found in hot springs containing hydrogen sulphide obtain energy by oxidizing inorganic sulphur. Organisms which obtain their energy from chemicals through oxidation reaction are called chemoautotrophs. The energy obtained by both photoautotrophs and chemoautotrophs is used to build food in form of complex molecules such as sugar, starch, protein, and lipids from carbondioxide.

Food manufacturing in plants (Photosynthesis)

Photosynthesis refers to a process whereby organisms containing chlorophyll and carotenoid pigments manufacture their own food in the form of carbohydrates from simple inorganic substances (carbon dioxide and water) using sunlight energy. Examples of photosynthetic organisms are plants and some bacteria (bacteriochlorophyll).

However, photosynthesis in plants differs from that of bacteria in terms of the products released. Unlike bacteria, plants release oxygen as a by product. In addition, photosynthesis in plants involves pigments such as chlorophyll, and carotenoids while bacterial photosynthesis uses bacteriochlorophylls in most cases. Bacteria therefore lack definite chloroplasts as opposed to plants which contain definite chloroplasts.

In green plants, photosynthesis can be summarised by the following equation.

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

Thus, the raw materials for photosynthesis are carbon dioxide and water. Plants obtain carbon dioxide from the atmosphere, which diffuses into the leaf through stomata. Water is normally absorbed from the soil into the plant body by the roots and transported via xylem tissue to the leaves which are the photosynthetic organs of plants. The light energy is trapped by chloroplasts which contain chlorophyll, the photosynthetic pigments of the leaves or stems in some plant species. One of the functions of light energy is photolysis of water, which refers to splitting of a water molecule in presence of light to produce hydrogen, oxygen, and electrons. These products of photolysis of water are required in the first stages of photosynthesis. The oxygen released during photosynthesis comes from water molecules. Two molecules of water produce one molecule of oxygen. Light is also important in producing biochemical energy in plants. This energy is required in fixing carbondioxide into phosphoglycerate which is rapidly converted into sugars and other forms of organic molecules, such as starch and protein for storage and cellular uses.

Ultimately, carbohydrates and other forms of organic molecules synthesized by autotrophs are the major sources of energy for all heterotrophs. Therefore, they are regarded as energy harvesters in all ecosystems.

The traditional equation of photosynthesis highlighted above does not illustrate the real situation of photosynthesis because, among other reasons, it gives the end product of photosynthesis as a hexose sugar. However, the end product is a triose sugar called 3-phosphoglyceraldehyde (3-PGAL). The equation shows that the source of oxygen is carbon dioxide. This is not correct because experiments using the two oxygen isotopes, O^{18} and O^{16}, show that the oxygen given off during photosynthesis comes from water, and not from carbon dioxide. Thus, more water enters the reaction so that some of it is evolved as a byproduct as revealed in a more accurate equation below. In this equation, CH_2O is an empirical formula for the carbohydrate formed by photosynthesis.

$$2H_2O + CO_2 \xrightarrow[\text{chlorophyll}]{\text{sunlight}} CH_2O + O_2 + H_2O$$

The site for photosynthesis

Photosynthesis takes place in the green parts of the plant leaves' mesophyll and bundle sheath cells which have chloroplasts. A chloroplast is a double membranous organelle found in the cytoplasm. Its matrix is called stroma which contains DNA, free ribosomes, membrane ribosomes, starch grains, lipid droplets and photosynthetic enzymes. The stroma also contains stacks of flattened sacs or membranes called thylakoids which contain photosynthetic pigments called chlorophyll and other accessory pigments. Thylakoids are stacked together to form column-like structures called grana (singular granum).

Structurally, chlorophyll is a long hydrocarbon chain with a hydrophobic (water hating) tail a complex ring of hydrophilic (water loving) head in the interior. Based on the structure, different types of chlorophylls can be discerned. (Figure 5.1)

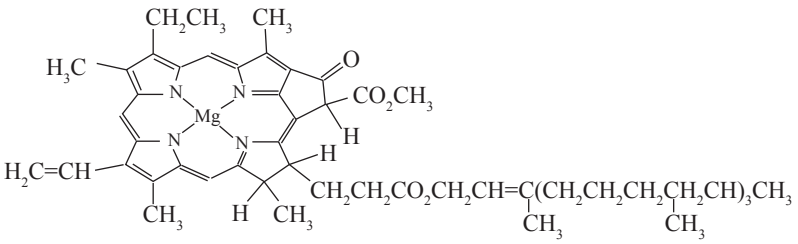


Figure 5.1 The Chemical structure of chlorophyll

There are several types of chlorophyll pigments, including chlorophyll *'a', 'b', 'c',* and *'d'*. Some organisms contain more than one type of chlorophyll pigment. However, chlorophyll a and b are more abundant in most plants while the majority of protoctists and cyanobacteria contain chlorophyll c and d. Chlorophyll absorbs red, blue and violet light but reflects green light. This makes all plants to appear green in color. Principally, the function of chlorophyll is to convert light energy into chemical energy. Other photosynthetic pigments are beta carotenes and phycobilins (found in organisms such as red algae and cyanobacteria), the red phycobilin is called phycoerythrobilin and the blue phycobilin is known as phycocyanin. They act as light energy transfer to the chlorophyll to be utilized in the photosynthesis process. Photosynthetic bacteria contain photosynthetic pigments called bacteriochlorophyll which are not contained in the chloroplast. This is because bacteria are single celled organisms, and the entire cell is an equivalent of a chloroplast. Bacteriochlorophyll are distributed in the membranes of the cytoplasm.

Mechanism of photosynthesis

The initial stage of photosynthesis can be viewed in two major phases or reactions and these are light reaction (light dependent reaction) which takes place in the thylakoid (grana) of the chloroplasts, and dark reaction (light independent reaction) which occurs in the stroma of the chloroplasts (for the structure of the chloroplast, refer to Chapter One, Figure 1.12). The light reaction is vital for the subsequent stage of photosynthesis (dark reaction), because it is during this stage when energy, electrons, and hydrogen are produced.

Light reaction (Light dependent reaction)

Light reaction stage of photosynthesis occurs in the thylakoids of the chloroplasts. Normally, chloroplasts are aligned in such a way that their thylakoids are held at right angle to the light source in order to maximize light absorption. Within the thylakoids, chlorophyll pigments are arranged in groups called photosystems, which are specialised form of chlorophyll that commonly exists in two forms namely; Photosystem I and Photosystem II. Chlorophyll photosystems are named in chronological order of their discovery, not in a way they are involved in light reaction.

Thus, photosystem I was discovered before photosysytem II. Photosystem I has a specialised form of chlorophyll called pigment 700 abbreviated as (P700) while Photosystem II has specialised form of chlorophyll pigment, 680 abbreviated as (P680). The numbers 700 and 680 stand for peak of wavelength of light which excite electrons in these pigments. This implies that the respective absorption peak for P700 and P680 is at the wavelength of 700 nm and 680 nm. Structurally, photosystem is a complex of chlorophyll, accessory pigments, proteins, and other molecules. They are important in the absorption and transfer of light energy through a series of reduction oxidation (redox) reactions.

Light reaction uses both photosystems I and II, which are embedded in the thylakoid membrane. Essentially, light reaction starts in photosystem II. Light energy (or photons) is absorbed by photosystem II. The absorbed energy is transferred to the chlorophyll centre causing electrons in the chlorophyll centre to be energised. The energised electrons are excited within the chlorophyll molecule; consequently, they move from ground to a higher energy state. This process is known as photo activation. The excited electrons are progressively passed on from one chlorophyll molecule to the subsequent one via a series of electron carriers to a nearby electron acceptor molecule found in the electron transfer chain. The movement of electrons can be in one direction because they do not move back to their original position in photosystem II but progress to photosystem I, the process which is described as non- cyclic photophosphorylation. On the other hand, the electrons can move back to their original position in photosystem I, in the process called cyclic photophosphorylation.

Non-cyclic photophosphorylation

The mechanism of non-cyclic photophosphorylation involves both photosystems I and II in a non-cyclic movement of electrons to produce ATP. When the chlorophyll in Photosystem II absorbs light, releases an excited pair of electrons which are transferred to a series of electron acceptor and carrier systems including cytochromes. As the electrons pass through different carrier systems, they release energy, but these electrons are not returned to their original position in the photosystem II rather they are handed over to the photosystem I. The energy released in a series of electron flow system is used by an enzyme called ATP synthase located in the thylakoid membrane to synthesize ATP by binding inorganic phosphate to ADP. This process is called phosphorylation, which literally means phosphate addition. However, the energy used in phosphorylation emanates from the sunlight. Hence, this ATP synthesis is precisely described as photophosphorylation. It should be noted that as the two excited electrons leave the photosystem II in the first stage after being activated by the light of wavelength 680 nm, they are replaced immediately by electrons released from the splitting of water molecules within the thylakoid. Water molecule splits into hydrogen ion or proton (H^+), oxygen and two electrons ($H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$). This process is called photolysis, because it only occurs in the presence of light. Thus, oxygen does not come from carbondioxide, but from the split of water molecules.

The chlorophyll of photosystem I is also activated and absorb light energy of the wavelength 700 nm. The absorbed energy excites the electrons, causing them to move from Photosystem I and transfer through a series of electron acceptor and carrier molecules, including Ferredoxin and ferredoxin-NADP reductase. As these electrons move through the carrier systems, they lose their energy but they are not returned to their original position, instead they are handed to $NADP^+$, where together with hydrogen proton (H^+) from photolysis of water, reduce $NADP^+$ to $NADPH_2$, also written as $NADPH^+$ or $NADPH + H^+$, as indicated by the following equation:

$$NADP^+ + 2H + 2e^- \longrightarrow NADPH + H^+$$

The light energy is now stored in the NADPH molecule which accumulates in the stroma to be used in the dark reaction (Figure 5.2).

NADP is therefore important in maintaining the flow of electrons in the thylakoid membrane as it is the final electron acceptor.Therefore, the normal flow of electrons can be inhibited, if this electron acceptor is limited.

Thus, the synthesis of ATP in this way is described as a non-cyclic photophosphorylation, because the electrons from photosystem II move in one direction. They do not move back to their original molecule, instead they move through different electron carriers, and they are taken up by photosystem I to fill the gap of the lost electrons used to reduce NADP. The formed ATP and NADPH are used in the Calvin cycle or dark reaction to produce carbohydrates while the oxygen gas from photolysis of water is released into the air as a byproduct.

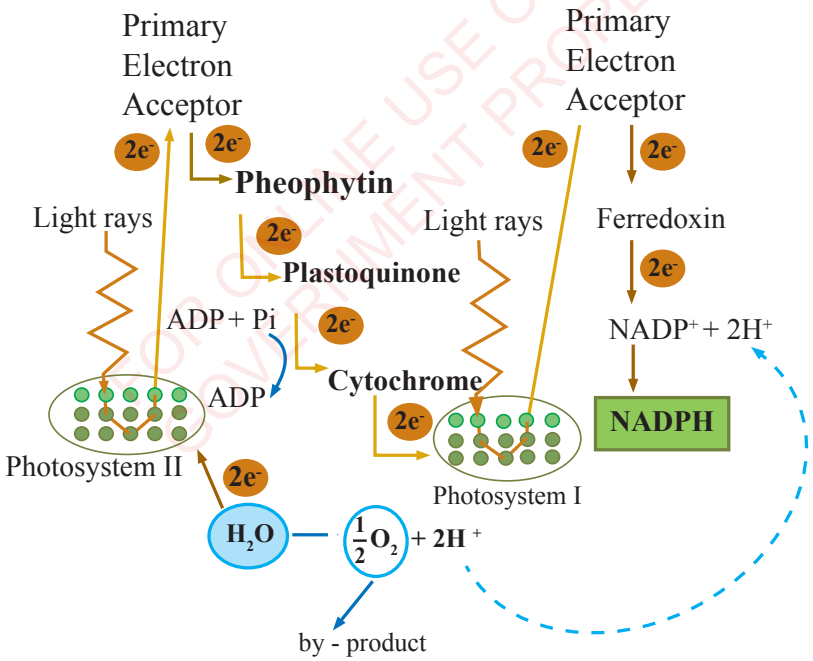


Figure 5.2 Non-cyclic photophosphorylation

Cyclic photophosphorylation

Cyclic photophosphorylation involves production of ATP which uses photosystem I but not photosystem II. This begins with photo activation of photosystem I through which the electrons are excited and pass on to a chain of electron carriers. These electrons travel back along a chain of carriers to their original position in photosystem I (Figure 5.3). As electrons travel back, they release energy which is utilised to bind inorganic phosphate to ADP forming ATP with the aid of ATP synthase. In this cycle, only ATP is produced, but NADPH and oxygen are not produced.

The amount of ATP required in Calvin cycle is much higher than that produced in the non-cyclic photophosphorylation. This makes the cyclic photophosphorylation important to balance the ATP deficit without increasing NADPH.

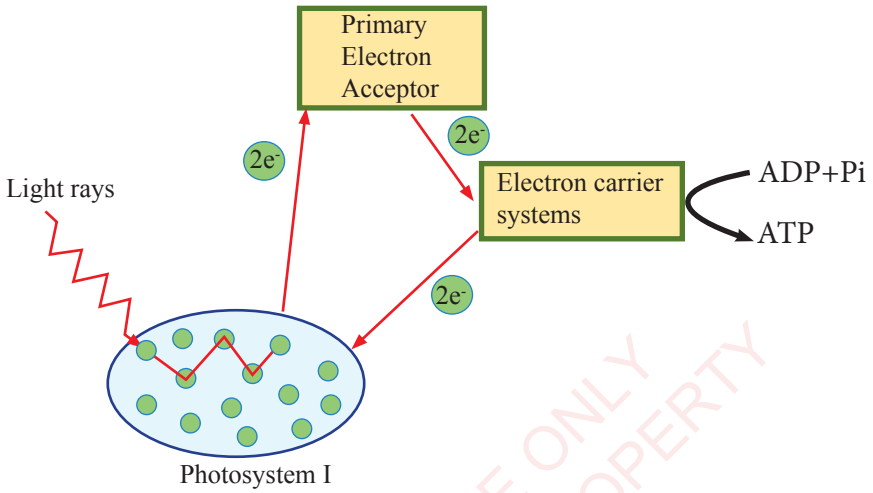


Figure 5.3 Cyclic photophosphorylation

Table 5.1 Differences between cyclic and non-cyclic photophosphorylation

Cyclic photophosphorylation	Non-cyclic photophosphorylation
Excited electrons always return to the original position or molecule.	Excited electrons do not return to the original position or molecule.
It involves only one photosystem (P700).	It involves two photo systems (P700 and P680).
Photolysis of water does not occur.	Photolysis of water occurs.
Reduced compounds are not formed; the only product is ATP.	Reduced compounds especially NADPH are formed together with ATP.
The final destination of electrons is photo system I.	The final destination of electrons is NADP.
The first source of electrons is photosystem I.	The first source of electrons is water.
Oxygen is not produced.	Oxygen is produced.

Activity 5.1 Experiment to prove the importance of light during photosynthesis

Materials

A healthy potted plant, petri dish or white tile, a beaker containing water, forceps, hot water bath, a piece of wire gauze, tripod stand, burner, match box, alcohol (90% ethanol), strip of black paper (carbon paper), Iodine solution, and clips (Figure 5.4).

Procedure

a) Take a potted plant and keep it in a dark place for 2-3 days so that the leaves get destarched.
b) Cover part of one of its leaves with a strip of black paper. Make sure that you cover both the lower and the upper sides of the leaf to prevent the entry of light.
c) Place the plant in sunlight for 3-4 hours.
d) Detach the selected covered leaf and remove the black paper covering it.
e) Place the detached leaf in the beaker containing water. Boil it for about 10 minutes.
f) Take out the leaf and boil it in boiling 90% ethanol in the hot water bath for 10 minutes.
g) Take out the leaf and wash it under running water to remove traces of ethanol and softening the tissues.
h) Spread the leaf on a petri dish or white tile and put a few drops of Iodine solution on it. Observe the changes in colour.

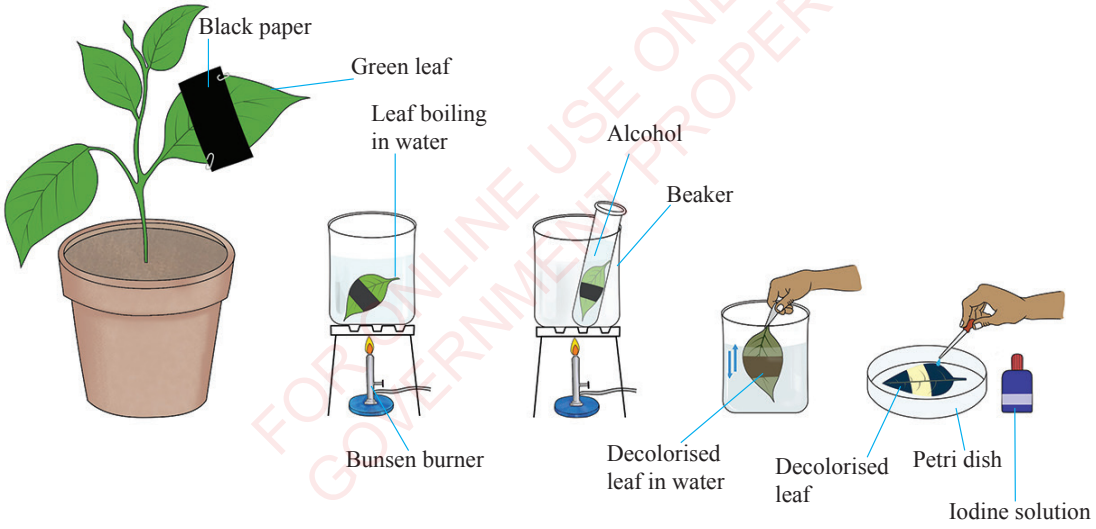


Figure 5.4 Experiment to show the importance of light during photosynthesis

Questions

1. Why was it important to destarch the leaf before starting the experiment?
2. What was the reason for covering the leaf with a black paper?
3. What was the reason of boiling the leaf in alcohol?
4. Which colour was observed after adding Iodine solution on a boiled leaf?
5. What does the observed colour indicate?

Exercise 5.1

1. Explain how plants obtain light energy and convert it to biochemical energy.
2. Briefly explain the importance of cyclic photophosphorylation in photosynthesis.
3. Differentiate cyclic from non-cyclic photophosphorylation.

Dark reaction (Light independent reactions)

Dark reaction does not require light energy, and it takes place in the stroma of the chloroplasts. The overall purpose of dark reaction is to convert carbon dioxide from the atmosphere into carbohydrates or sugars which are used to power primary activities in plants and build their structures. The process of converting carbon dioxide into carbohydrates requires energy produced by ATP and the reducing power obtained from NADPH both produced from the light reaction. The fact that these chains of reactions are described as dark reactions does not imply that the reactions cannot take place in the presence of light. It simply means that light energy is not a vital factor in this phase of photosynthesis. The vital factor here is atmospheric carbondioxide, and the products of light reaction are ATP and NADPH. Dark reaction is therefore a synthetic stage of photosynthesis. However, such reactions, as cited earlier are energetically dependent on light reactions. The dark reactions involve a chain of enzyme controlled reactions described by Melvin Calvin, Andrew Benson and James Bassham in 1946-1953. These reactions involve a full cycle of reactions also called the Calvin cycle or Calvin-Benson cycle; named after Calvin and Benson. The Calvin cycle (Figure 5.5) has three major phases which are carbondioxide (CO_2) fixation, reduction of glycerate phosphate (GP), also called phosphoglyceric acid (PGA), and regeneration of ribulose biphosphate (RuBP).

Carbon dioxide fixation

Carbondioxide (CO_2) used in dark reaction comes from the atmosphere. It diffuses into the plant tissue via stomata pores located in the leaves or stems in some plants such as cactus. The absorbed CO_2 is attached to a 5-carbon compound called RuBP to form unstable 6-carbon compound by carboxylation reaction. The 6-carbon molecule quickly splits into two 3-carbon energy rich molecules called glycerate phosphate which, in principle are carboxylic acid, 3-phosphoglyceric acid (3-PGA or PGA).

RuBP is therefore called the carbon dioxide acceptor due to its ability to accept or combine with carbondioxide. The reaction is catalysed by Ribulose 1,5-biphosphate carboxylase (Ribulose

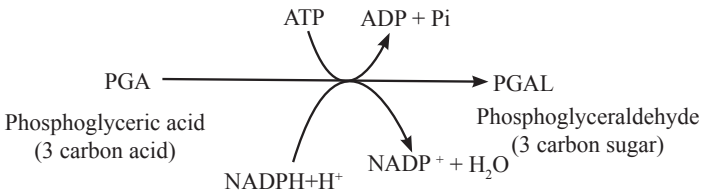
biphosphate carboxylase) enzyme, which is abundant in the stroma of the chloroplast, and it is usually abbreviated as RuBP carboxylase, or RuBisCo, or Rubisco, or RuBPCase, or RuBPco. The PGA are the first stable product of photosynthesis and their formation marks the first major step in the fixing of carbon dioxide in green plants and photoautotrophic bacteria into energy rich molecules.

$$\underset{(5C)}{RuBP + CO_2 + H_2O} \xrightarrow{\text{RuBP Carboxylase}} \underset{(3C)}{2PGA}$$

Carboxylation is followed by a chain of reactions which involve reduction of PGA

Reduction of phosphoglyceric acid (PGA)

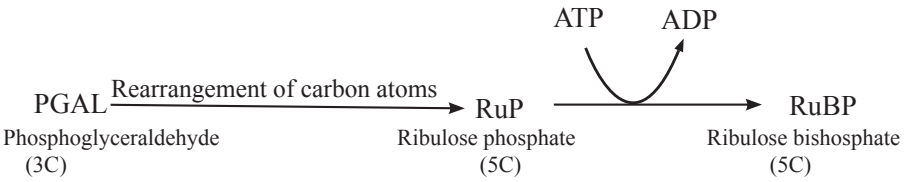
The reduction reaction begins when energy supplied by ATP and the reducing power of NADPH are used to remove oxygen from the PGA. This reduction reaction produces a 3-phosphoglyceraldehyde (3-PGAL or PGAL) also called glyceraldehyde phosphate (GP), which is a triose sugar (3-Carbon sugar) containing phosphate group.



The difference between the PGA and the PGAL is that, the former is a 3-carbon acid (-COOH) while the latter is 3-carbon aldehyde (-CHO), therefore, PGAL is the first carbohydrate in photosynthesis which is a sugar with more chemical energy than PGA. It should be noted that the ATP and NADPH utilised in this phase of Calvin cycle are obtained from the light dependent reactions. The ADP and $NADP^+$ return to the thylakoids to be converted back to ATP and NADPH, respectively, by the light reactions. One of the PGAL molecules is set aside to be used as a building block of glucose and other molecules such as sucrose, starch, cellulose, amino acids, fatty acids and glycerol. These products are used for various biological roles including respiration, building plant cell wall, building the body, and component of cell membranes. The majority of PGAL molecules will be forwarded to the third phase of the Calvin cycle to regenerate RuBP consumed in the first reaction of carbon dioxide fixation.

Regeneration of RuBP

RuBP is an important molecule utilised in the synthesis of sugars, therefore, it is necessary for plants to produce enough of it for synthesis of more sugars and other vital molecules. RuBP is regenerated from PGAL, which combines with Ribulose phosphate (RuP) molecules as summarized in the equation below. This process involves a complex series of rearrangement of carbon atoms between sugar phosphates to generate 5-carbon sugar from 3 carbon-sugar. The formed 5-carbon sugar (RuP) is then phosphorylated by the remaining ATP from light reaction to generate ribulose bisphosphate (RuBP). The produced RuBP can combine with the additional carbon dioxide molecules and continue to the Calvin cycle reaction.



Note that in order to form a glucose molecule, the cycle has to run six times because each turn of the cycle adds only one carbon from the incoming carbon dioxide to form two molecules of PGAL, that is, six molecules of carbon are consumed to synthesize twelve molecules of PGAL, where by only two molecules of PGAL are used to make carbohydrate (glucose) while ten molecules are used to regenerate 6 molecules of RuBP in the regeneration phase (Figure 5.5).

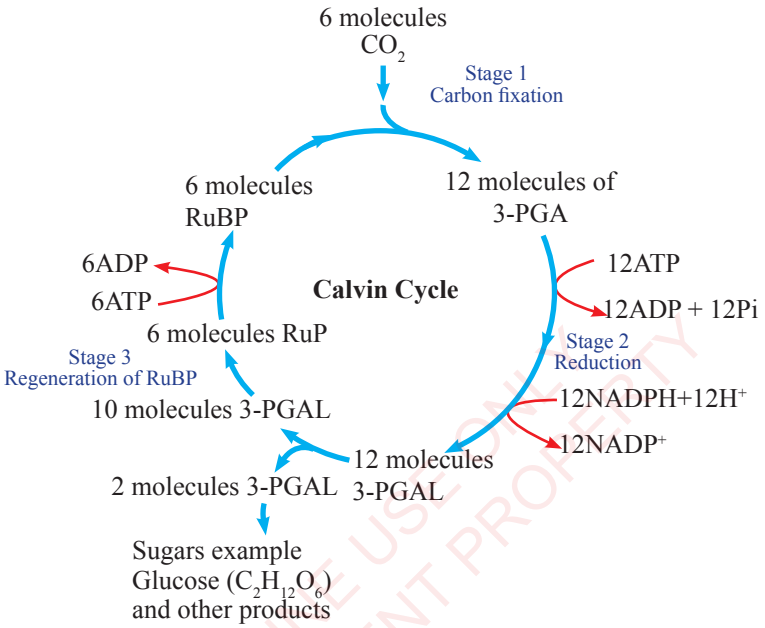


Figure 5.5 The Calvin cycle

Exercises 5.2

1. Explain how light and dark reactions of photosynthesis are interdependent.
2. Describe the steps involved in the conversion of phosphoglyceric acid into sugar.
3. What is the fate of PGAL formed in photosynthesis?
4. Naming Calvin cycle as a dark reaction is sometimes misleading. Substantiate.

C_3 and C_4 plants

Different plants use different pathways to fix carbon during the process of photosynthesis. Fixing carbon is the way plants remove carbon from atmospheric carbon dioxide and turn it into organic molecules like carbohydrates. Basing on the first product of photosynthesis just after carboxylation, plants are grouped into C_3 and C_4 plants.

C_3 plants

In some plants, the first product of photosynthesis immediately after carboxylation is a 3-phosphogylceric acid (3-PGA). These plants fix carbon dioxide, following the Calvin cycle as explained in the preceding section. Plants which yield a 3-PGA, as the first product after carboxylation, are described as C_3 plants. Fixation of carbon dioxide occurs in the chloroplasts of the bundle sheath cells. C_3 plants account for approximately 85% of all plants including Bryophytes, ferns, most grasses, and trees. They also include crops such as cotton, tobacco, spinach, soybean, and cereal grains (rice, wheat). This implies that most food that we eat comes from C_3 plants. C_3 plants perform well in temperate conditions, but they suffer photorespiration which is also called oxidative photosynthetic carbon cycle or C_2 photosynthesis in hot and dry conditions.

Photorespiration

This is a condition which occurs when carbon dioxide concentration in the chloroplast drops below 50 ppm while the level of oxygen is relatively higher. Under this condition, oxygen and carbon dioxide compete for the same active site on RuBP carboxylase enzyme. This in turn triggers the enzyme to utilize oxygen to oxidise RuBP to form one molecule of 3-PGA (three carbon) and 2-phosphoglycolate (two carbon compound) instead of acting on carbon dioxide to produce two molecules of PGA (three carbon).

$$\underset{5C}{O_2 + RuBP} \xrightarrow{\text{RuBP carboxylase}} \underset{2C}{\text{Phosphoglycolate}} + \underset{3C}{\text{PGA}}$$

Since the reaction is an oxygenation reaction, the enzyme RuBP carboxylase is also known as RuBP oxygenase. There is no energy-rich compound produced, since 2-phosphoglycolate produced cannot enter the Calvin cycle; rather it enters in the conversion pathways and use NADPH and ATP to generate PGA, hence decrease in yield. Decreased concentration of carbon dioxide occurs during dry or hot conditions because the stomata pores through which carbon dioxide diffuses into the plant normally close to minimise water loss through transpiration under such conditions. The global increase in temperatures and drought conditions in some places emanating from climatic changes is likely to impact C_3 plants more than C_4 plants, which are more efficient photosynthetically. Photorespiration involves a complex network of enzyme reactions which exchange the cellular metabolites between three organelles, namely chloroplasts, leaf peroxisomes and mitochondria (Figure 5.6). The formed 2-phosphoglycolate is dephosphorylated by removing of phosphate group (Pi) to form glycolate which leaves the chloroplast to the peroxisome. In the peroxisomes, Glycolate is oxygenated to give glyoxylate and in this process hydrogen peroxide gas is evolved. The formed glyoxylate is converted into glycine, then this product enters the mitochondrion in which it is converted into serine through the series of reactions. The produced serine is transported to the peroxisome and it is converted into hydroxypyruvate then to Glycerate (Glyceric acid). The glycerate formed is transported to the chloroplasts, and with the help of ATP it is converted into 3-PGA by adding Pi in its carbon number 3.

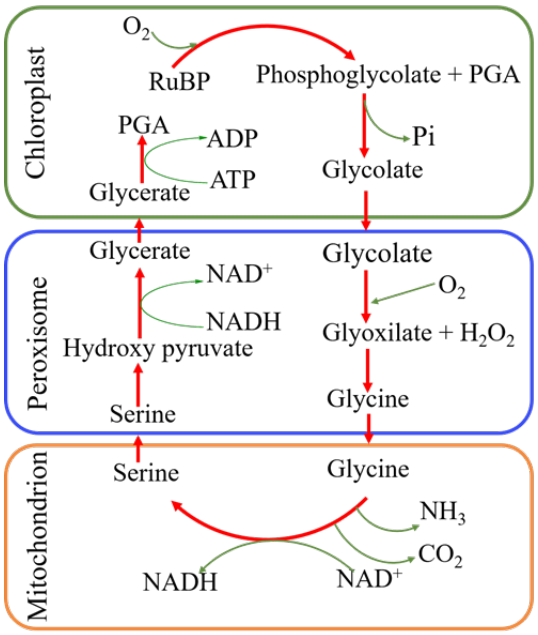


Figure 5.6 Photorespiration pathway

C_4 plants

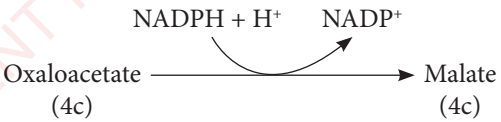
Photosynthesis in most tropical and subtropical plant species, such as maize and sugar cane yields a 4-carbon compound called oxaloacetate (oxaloacetic acid) after carboxylation, and they are thus referred to as C_4 plants. C_4 plants have 2 major biochemical pathways (Figure 5.7). The first pathway involves transporting carbon dioxide from the mesophyll to the chloroplast of the bundle sheath, a pathway which was described in 1966 by Hatch and Slack. This pathway is therefore called Hatch-Slack pathway in honor of these two Australian scientists. The second pathway in C_4 plants is the normal C_3 pathway (Calvin cycle) which commences once the carbon dioxide is released in the bundle sheath cells. C_4 pathway is characterised by four major events: fixation of carbon dioxide in the mesophyll cell, shunting of malate, regeneration of carbon dioxide acceptor, and re-fixation of carbon dioxide in the bundle sheaths.

a) Fixation of carbon dioxide in the mesophyll cell

Carbon dioxide fixation occurs in the mesophyll cells and involves carbondioxide acceptor known as phosphoenolpyruvate (PEP). The carbon dioxide is attached to PEP to form a 4-carbon molecule called oxaloacetate. This carboxylation reaction is catalysed by phosphoenolpyruvate carboxylase (PEP carboxylase) enzyme. In this reaction, therefore, hydrogen and carbon dioxide are added to PEP to form oxaloacetate. The PEP carboxylase has relatively higher carbon dioxide affinity compared to RuBP carboxylase which is used in carboxylation in C_3 plants.

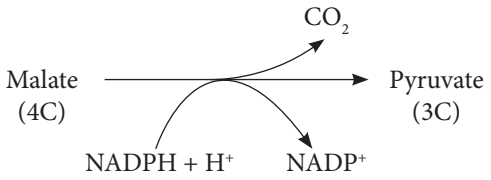
$$PEP + CO_2 \xrightarrow{\text{PEP carboxylase}} \text{Oxaloacetate}$$

The oxaloacetate formed is further converted into another 4-carbon compound called malate



b) Shunting of malate

The shunting commences as malate gets streamed to chloroplasts of the bundle sheath cells through small pores called plasmodesmata, found in the cell wall. In the chloroplasts, malate dissociates, yielding hydrogen, carbon dioxide and a 3-carbon acid called pyruvate (pyruvic acid).



This ultimately leads to high accumulation of carbon dioxide in the bundle sheaths. It should be noted that shunting of malate is necessary to ensure movement of carbon dioxide and hydrogen from the mesophyll to the bundle sheath cells. The hydrogen liberated reduces NADP into NADPH which will be used in carbon dioxide re-fixation. The stages (a) and (b) accomplish the Hatch-Slack pathway.

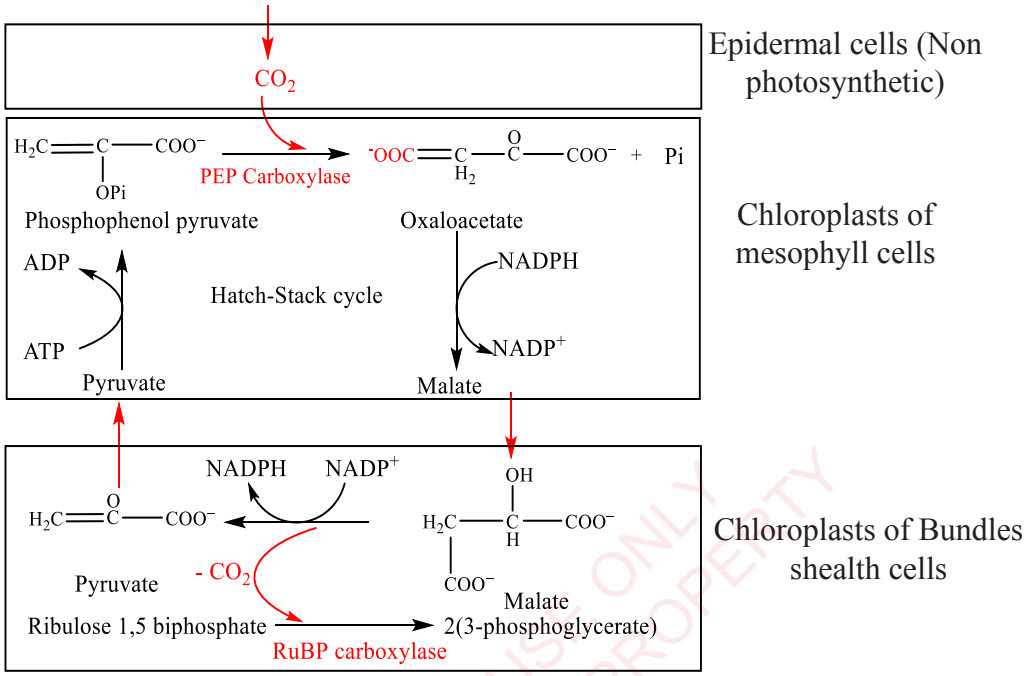
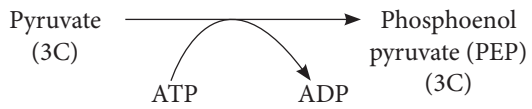


Figure 5.7 The Hatch-Slack pathway

c) Regeneration of carbon dioxide acceptor

Pyruvate generated in the shunting of malate as explained in (b) is converted back into PEP by the addition of organic phosphate supplied by ATP.



d) Re-fixation of carbon dioxide in bundle sheaths

The released carbon dioxide from the dissociation of malate (refer to the shunting of malate above) enters the C_3 pathway (Calvin cycle). At this stage, the carbon dioxide is accepted by RuBP to produce 3-PGA, a reaction is catalysed by RuBP carboxylase enzyme. The NADPH will reduce 3-PGA to sugar (3-PGAL) in the same way as C_3 plants.

Generally, the C_4 pathway consumes more energy (ATP), and it is more efficient in

yielding carbon dioxide compared to the C_3 pathway. However, ATP consumption is not a problem, considering that much of it is produced during light reactions. The fact that the C_4 pathway produces high yields under high concentration of carbon dioxide makes photosynthesis in C_4 plants more efficient in carboxylation compared to C_3 plants which under certain conditions such as hot, dry conditions undergo photorespiration. The PEP carboxylase in the mesophyll of C_4 plants has a high affinity to carbon dioxide, and it does not get competitively inhibited by oxygen to cause photorespiration. Although carbon dioxide is a limiting factor in photosynthesis, C_4 plants can photosynthesize, even if the stomata are closed due to the presence of high levels of carbon dioxide in the bundle sheath cells, just about 20 to 120 times higher than normal.

Differences between C_3 and C_4 plants

The major differences between these two types of plants are evident in the photosynthesis process. Generally, the basic metabolism of the C_3 and C_4 plants is similar, but the latter is more complex. The C_4 plants are therefore evolutionarily more advanced than C_3 plants (Table 5.2).

Table 5.2 Differences between C_3 and C_4 plants

C_3 plants	C_4 plants
The first product in carbon dioxide fixation is a 3-carbon compound called phosphoglyceric acid.	The first product in carbon dioxide fixation is a 4-carbon compound called oxaloacetic acid.
Photosynthesis is limited by low levels of atmospheric carbon dioxide, hence photorespiration may occur in a limited supply of carbon dioxide.	Photosynthesis is not limited by low levels of atmospheric carbon dioxide, hence photorespiration does not occur.
Carboxylation reaction is accomplished by the enzyme RuBP carboxylase to fix carbon dioxide.	Carboxylation reaction is accomplished by the enzymes RuBP carboxylase and PEP carboxylase to fix carbon dioxide.
The carbondioxide acceptor is a 5-carbon compound called RuBP.	The carbondioxide acceptors are the 3-carbon compound (PEP) and the 5-carbon compound (RuBP).
Carbondioxide fixation occurs in bundle sheath cells only.	Carbondioxide fixation occurs in both, mesophyll cells and bundle sheath cells.
They are less efficient in fixing carbon dioxide.	They are more efficient in fixing carbon dioxide.
They have only one type of chloroplast in their leaf bundle sheath cell.	They have two types of cells, each with its own type of chloroplast. (Kranz aatomy).
They do not tolerate hot and dry conditions. They are adapted to cool and wet environment.	They tolerate both hot and dry conditions.
Example of C_3 plants: soybeans spinach, rice and grasses.	Example of C_4 plants: millet, sorghum and sugar cane.

Exercise 5.3

1. Describe how C_4 plants are adapted to synthesize sugars in the tropical and subtropical climates.
2. Using your knowledge of C_3 and C_4 plants, explain which plants are more vulnerable to climate changes.
3. Differentiate C_3 plants from C4 plants.

Factors affecting the rate of photosynthesis

For photosynthesis to take place efficiently, certain conditions must be met, and raw materials must be present. The process of photosynthesis is influenced by both internal and external factors.

a) Internal factors

The internal factors which are also called plant factors are chlorophyll concentration, enzymes, inhibitors, and leaf structure and position.

Chlorophyll concentration

Chlorophyll is a green photosynthetic pigment located in the chloroplast, especially in the grana. Chlorophyll is responsible for trapping light energy during light reaction. When chlorophyll concentration in the leaves is very low, the rate of light reaction will be reduced, because only a little amount of light will be trapped for the reaction, resulting in reduction in the rate of photosynthesis. Low concentrations of chlorophyll in plant leaves can be caused by several factors, such as mineral deficiency, ageing, lack of light and diseases such as fungal diseases or infections.

Inhibitors

An inhibitor is a substance or factor which may slow down the rate of reaction. For example, many herbicides such as Dichlorophenyl Dimethyl Urea (DCMU) interfere with the electron flow in the chloroplast; thus, inhibit the light reaction, and hence no photophosphorylation. In addition, a relatively higher concentration of oxygen (above 21%) in the atmosphere tends to inhibit the rate of photosynthesis, because it lowers the amount of carbondioxide available to the plant.

Leaf structure and position

Leaf is a photosynthetic organ of a plant. It contains chloroplasts, which are organelles for food synthesis. Leaves have special adaptation to enhance carbon dioxide and light absorption for photosynthesis. For example, they have a broad surface area exposed to light illumination and thin leaves with large surface area absorb more light than small and thick leaves. Carbon dioxide penetrates more quickly in thin leaves than in thick leaves. Additionally, leaves with thin and transparent epidermis allow more light to reach the chloroplasts. Furthermore, leaves, particularly of most tropical plant tree species, are positioned at a certain angle which is normally more or less vertical. This reduces excessive light interception and temperature on the leaf. Reducing this natural angle of leaf may be detrimental to the chloroplast because it increases light interception and excessive temperature. Thus, maintaining high leaf angle orientation in tropical trees is necessary in reducing excessive light interception and leaf temperature to protect chlorophyll from photo damage due to excessive light. This in turn

enhances photosynthetic activity and helps to sustain high plant productivity.

Enzymes

Photosynthesis is an enzyme controlled process. For example, the enzyme PEP carboxylase is crucial in the fixation of carbon dioxide in the mesophyll cells. Similarly, RuBP carboxylase is an important enzyme necessary for carbon dioxide fixation in bundle sheath cells during dark reaction. Another enzyme is ATP synthase found in the thylakoid membrane. This enzyme is vital for ATP synthesis during photophosphorylation process. These enzymes perform their role actively under optimal condition below which they become inactive or above which they are denatured. If the enzymes are inactive, the rate of photosynthesis proceeds very slowly. In contrast, when the enzymes are very active, the rate of photosynthesis becomes very high.

Activity 5.2 Investigating the role of chlorophyll in photosynthesis

Materials

Variegated plant, Iodine solution, beaker, ethanol, water, and white tile.

Procedure

a) Take a potted plant with variegated leaves which has been exposed to sunlight for three to four hours.

b) Take one leaf and draw its diagram indicating the pattern of the colour of the patches.

c) Place the leaf in the beaker containing hot water and boil it for about 10 minutes.

d) Take out the leaf and place it in boiling ethanol in a water bath for about 10 minutes.

e) Remove the leaf from ethanol and wash it with running water.

f) Place the leaf on a white tile and add a few drops of Iodine solution.

g) Record any observable changes.

h) Draw a diagram of the leaf showing the colour pattern after being stained with iodine solution.

i) Compare the colour pattern of the patches with that of the original leaf in b).

Safety precaution

Avoid direct flame near ethanol because it is highly inflammable.

Questions

1. Why was the variegated leaf used in the above experiment?
2. Explain your observations.
3. What was the reason for boiling the leaf in ethanol?
4. From the observations made in the experiment, what is the role of chlorophyll in the leaf?

b) External factors

The external factors which are also termed as environmental factors include; atmospheric carbon dioxide concentration, water availability, wind, temperature, mineral and nutrients supply as well as light.

Atmospheric carbon dioxide concentration

The average concentration of carbon dioxiode in the atmosphere is about 0.03%. As the concentration of carbon dioxide increases from the average value, it also increases the rate of photosynthesis. Carbon dioxide is required in light independent reactions, but the concentration above 0.1% can damage plant leaves. On the other hand, low levels of carbon dioxide tend to limit the rate of photosynthesis. It should be noted that, C_3 plants are affected by low concentration of carbon dioxide in the atmosphere, while C_4 plants are efficient in utilising carbon dioxide even when the concentration in the atmosphere is low.

Temperature

Within the optimum range of temperature, the rate of photosynthesis tends to double for every 10 ^oC rise of temperature. For example, the optimum temperature for plants that survive in temperate climates is 25 ^oC. The temperature above 35 ^oC usually causes denaturation of enzymes catalyzing photosynthesis in both, dark and light reactions, leading to slowing down, or stopping of photosynthesis. In low temperature such as below 10 ^oC, enzymes catalysing photosynthesis become inactive, hence lower its rate.

Nutrients supply

Minerals such as magnesium and nitrogen are components of chlorophyll. Deficiency of these minerals reduces the rate of photosynthesis because the plant lacks enough chlorophyll molecules for trapping enough light energy.

Water availability

Water is one of the essential raw materials for photosynthesis. It also plays other roles in the plant body such as translocation of minerals and gases as well as products of photosynthesis. Shortage of water leads to wilting of plant leaves which in turn causes closing of the stomata. This results into a reduced diffusion rate of carbon dioxide into the chloroplast, and hence a decreased rate of photosynthesis. Additionally, water shortage causes cells to become flaccid; thus they cannot function well and this affects the translocation of synthesised products.

Light

The effect of light on the rate of photosynthesis can be described on the basis of its quality (light wavelength) and quantity (light intensity).

Light quality (wavelength of colours). Photosynthesis usually occurs when green plants absorb light within a limit of visible light spectrum. The most effective range is within a red-orange band (600- 700 nm) and a blue-violet band (400-500 nm). The central band is also effective, but less than others because the chlorophyll molecules show very little absorption of light in this region. Maximum light absorption corresponds to the maximum rate of photosynthesis.

Light intensity. The rate of photosynthesis varies proportionally to light intensity. However, at a certain point called light saturation point, the rate of photosynthesis reaches its maximum and therefore attains constancy. Any further increase in light intensity brings no effect on the

rate of photosynthesis, if other factors are limiting. However, unless the plant is adapted to high light intensity, the chlorophyll might undergo bleaching. Leaf adaptation to very high light intensity includes presence of thick cuticle and hairs. Light intensity varies with location and seasons of the year. In the tropical and subtropical areas, light intensity is higher than in the temperate areas. Light intensity also decreases during rainy seasons due to cloud cover.

During photosynthesis, the plant consumes carbon dioxide via respiration as it eliminates oxygen, which is important for respiration. A point is reached when light intensity causes the rate of photosynthesis to balance with that of respiration. This means that the rate of carbon dioxide production from respiration is equals to that of carbon dioxide consumption in photosynthesis. This is called a compensation point of a plant, at which net gain of atmospheric air is zero (Figure 5.8).

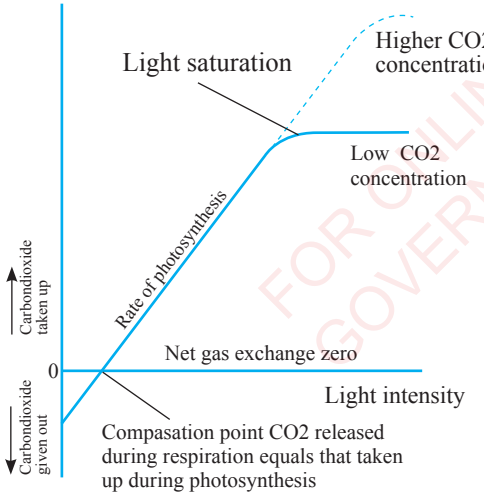


Figure 5.8 The light intensity and compensation point

Wind velocity

Wind moving at high speed reduces the rate of photosynthesis because strong wind usually facilitates transpiration and hence affects the availability of water. Therefore, speedy wind reduces the amount of water available as the raw material for photosynthesis, and consequently reduces the rate of photosynthesis.

Exercise 5.4

1. Describe photosystem I and photosystem II in green plants and show how they are involved in producing NADPH and ATP during light reaction of photosynthesis.
2. Explain how plants such as sugarcane and sorghum are adapted to overcome photorespiration.
3. Explain how light quality and intensity affect the rate of photosynthesis.

5.3 Heterotrophic nutrition

Heterotrophic nutrition is the mode of nutrition in which an organism feeds by taking in organic substances made by other organisms. Organisms that obtain organic food substances from other organisms are termed as heterotrophs. Examples: animals, fungi, some protoctists and most monerans.

Food materials synthesized by autotrophs are in the form of complex molecules, which contain chemical energy locked in their bonds. Heterotrophs ingest large molecules and they require a digestive

system to break down large food molecules into simpler forms which can be absorbed for utilization in their bodies. Furthermore, they require energy to carry out life processes like cellular metabolism. Some bacteria form a special group of heterotrophs called photoheterotrophs. These bacteria can utilize organic raw materials to synthesize their food in the presence of light energy. Animals, including human beings utilize six different types of nutrients for proper body functioning. These nutrients can be categorized into two major groups: organic and inorganic nutrients. Organic nutrients include carbohydrate which supply energy for body functions, fats or lipids which constitute the major part of cell membrane and stored form of body energy, proteins for growth and repair of body tissues, and vitamins for body defence. Inorganic nutrients include water which is a vital fluid required for chemical reactions to take place and transport of materials and minerals which are essential for proper body functioning.

Types of heterotrophic nutrition

Heterotrophs obtain their food by various ways. There are three forms of heterotrophic nutrition, namely saprophytic, symbiotic, and holozoic nutrition.

a) Saprotrophic nutrition

This type of nutrition is also referred to as saprophytic nutrition. The term saprotroph comes from two Greek words; *sapros* and *trophos* where *sapros* means 'rotten' and *trophos* means 'feeder.' This type of nutrition involves organisms feeding on soluble organic compounds obtained from dead or decaying bodies of other organisms, mainly plants and animals. Digestion is accomplished by producing extracellular digestive enzymes which reduce the tissues of the dead or decaying organisms into solution form which can be readily taken up. Most bacteria and fungi, such as *Mucor, Rhizopus,* and yeast are saprotrophs.

b) Symbiotic nutrition (Symbiosis)

The term symbiosis literally means 'living together.' Symbiosis is therefore a natural association between two or more different species. There are three common types of symbiotic relationships which are mutualism, commensalism and parasitism.

Mutualism. This refers to the association between two living organisms of different species in which both benefit. Therefore, the association or relationship is beneficial to both partners. The cellulose digesting bacteria living in the ruminant herbivores is an example of organisms which show a mutualistic relationship. These bacteria can only survive in anaerobic conditions found in a ruminant's alimentary canal, and they feed on cellulose contained in the host's diet. On the other hand, ruminants cannot digest cellulose directly but, as the cellulose digesting bacteria feed on the cellulose, they convert it into simple compounds which can be digested, absorbed and assimilated by the ruminants. Mutualistic form of symbiotic nutrition is also evident between leguminous plants and nitrogen fixing bacteria, where by the bacteria accommodated within the root nodules of these plants fix nitrogen from the air by converting it into nitrogen useful compounds such as nitrates. These

nutrients are required by plants for their growth and development, while on the other hand, the bacteria benefit by getting shelter and synthesised nutrients from the plants. Algae and fungi form a mutualistic association called lichen. In this relationship algae synthesise food and supply some to the fungi while the fungi cover the algae and protect it from desiccation. Also, fungi and roots of vascular plants form a mutualistic association called mycorrhizae. The role of fungi in this relationship is to increase the surface area for the plant roots absorption of nutrients. The plant supplies some of the manufactured food to the fungi which normally cannot photosynthesise its food.

Commensalism. Commensalism is a close association between two living organisms of different species in which one organism benefits and the other organism neither benefits nor is harmed. For example, cattle egrets follow herds of cattle or buffalo and feed on insects disturbed by the animals. The cattle and buffalo are not harmed by the feeding activities of the cattle egret. Therefore, in this association one member (the cattle egret) benefits while the other (cattle or buffalo) neither benefits nor is harmed.

Parasitism. Parasitism is a close association between two organisms of different species, whereby one organism called a parasite benefits by obtaining its nutrients and shelter from another living organism called a host. Normally, the parasite may ultimately cause harm to the host but, in some cases, it can exist without killing the host. Some parasites such as tape worms and liver fluke live in the internal organs or tissues of the host body. These types of parasites are called endoparasites. On the other hand, some parasites such as ticks and bed bugs attach themselves on the surface of the body of their living host and suck fluids from them; and these are called ectoparasites. Both endoparasites and ectoparasites are highly adapted to their mode of nutrition. For example, most parasites have hooks and haustoria for attachment and sucking nutrients from the host.

c) Holozoic nutrition

Holozoic nutrition is a form of heterotrophic nutrition exhibited mainly by free living animals which have a specialized digestive tract, also called alimentary canal. The nutrition of this form involves several steps such as taking in solid or liquid food, followed by mechanical and chemical digestion in the alimentary canal. The digested food materials are reduced into simple forms, which can be absorbed and assimilated by body cells. Holozoic organisms include animals such as herbivores which feed on plants, carnivores which feed on living animals; omnivores which feed on both plants and flesh, and decomposers feeding on remains of dead animals and plants, or on dung and faeces. The undigested food is eliminated from the body while the digested soluble food molecules get absorbed and later assimilated to generate energy and some are incorporated into the body cells.

Holozoic nutrition in mammals

The food taken in by mammals in most cases is in solid form; therefore, it must be converted into simpler form, for it to be

absorbed and assimilated in their bodies. The holozoic nutrition involves ingestion, digestion, absorption, assimilation, and egestion.

a) Ingestion

This process involves taking in solid or liquid food into the gut or alimentary canal or gastrointestinal tract of an organism. It is aided by structures such as teeth, tentacles and claws through which food substance is taken into the mouth through eating or drinking.

b) Digestion

Digestion is the process of breaking down large biochemical compounds contained in food into smaller and soluble molecules that can easily be absorbed into the body. It involves mechanical and chemical digestion. Mechanical digestion involves the physical break down of the food into smaller pieces; and this begins in the mouth where the food is chewed and rolled by the tongue, while lubricated by the saliva before it is swallowed. The tongue, teeth and saliva are thus important in preparing the food from large particles into bolus which can easily be swallowed for subsequent digestion stages. The mastication of food from larger particles to small ones is necessary for reducing the food into fine particles which makes it easy to be swallowed as well as harnessing nutrients from the food during digestion. Additionally, mechanical digestion involves mechanical contraction of the gut, which pounds up and mixes the semi-solid foods.

Similarly, digestion process is done chemically by the action of digestive enzymes on smaller pieces to yield simpler molecules with suitable size for absorption by the epithelia cells. Chemical digestion is a complex process that involves a diversity of digestive enzymes secreted by the alimentary canal, which convert various food substances into simpler and absorbable form. For example, polysaccharides are broken down into monosaccharides; proteins are broken down into amino acids; and fats or lipids are broken down into fatty acids and glycerol.

c) Absorption

This is the uptake of the digested soluble products and other substances across the linings of the gut into the blood stream and lymphatic system. The soluble substances include vitamins and minerals. The small intestine is the site where digested foods are absorbed through diffusion or active transport. The inner wall of the small intestine; also called the mucosa is lined with microscopic finger-like projections called villi. The epithelial cells of the small intestine have microvilli. Both villi and microvilli have a role of increasing surface area for nutrients absorption. The villi are equipped with a network of blood capillaries and lymphatic vessels. Normally, the absorbed nutrients enter the blood vessels and are supplied to different body organs.

d) Assimilation

This is the process of incorporating and using the absorbed food molecules into the body. The digested materials, which are absorbed into the blood, are carried by the blood stream to the body cells and tissues for use in life processes such as

respiration, growth, repairing body tissues and maintaining good health. In addition, excess of such food materials may be stored for future use in the liver, muscles and adipose tissues.

e) Egestion

Egestion is the process of eliminating undigested food materials from the gut through the anus. This is the final stage in holozoic nutrition in mammals during which the undigested food materials or faeces are removed from the alimentary canal.

The process of digestion

Digestion in mammals such as human beings occurs throughout the alimentary canal. The alimentary canal in humans comprises of mouth, oesophagus, stomach, small intestine, large intestine (colon), caecum, rectum and anus (Figure 5.9). The alimentary canal is also associated with the accessory organs such as the liver, salivary glands, and pancreas, which assist in digestion. The wall of the alimentary canal has almost the same basic structure throughout its length. The wall is lined by the simple epithelium or glandular epithelium tissue and all parts of the gut contain circular and longitudinal muscles.

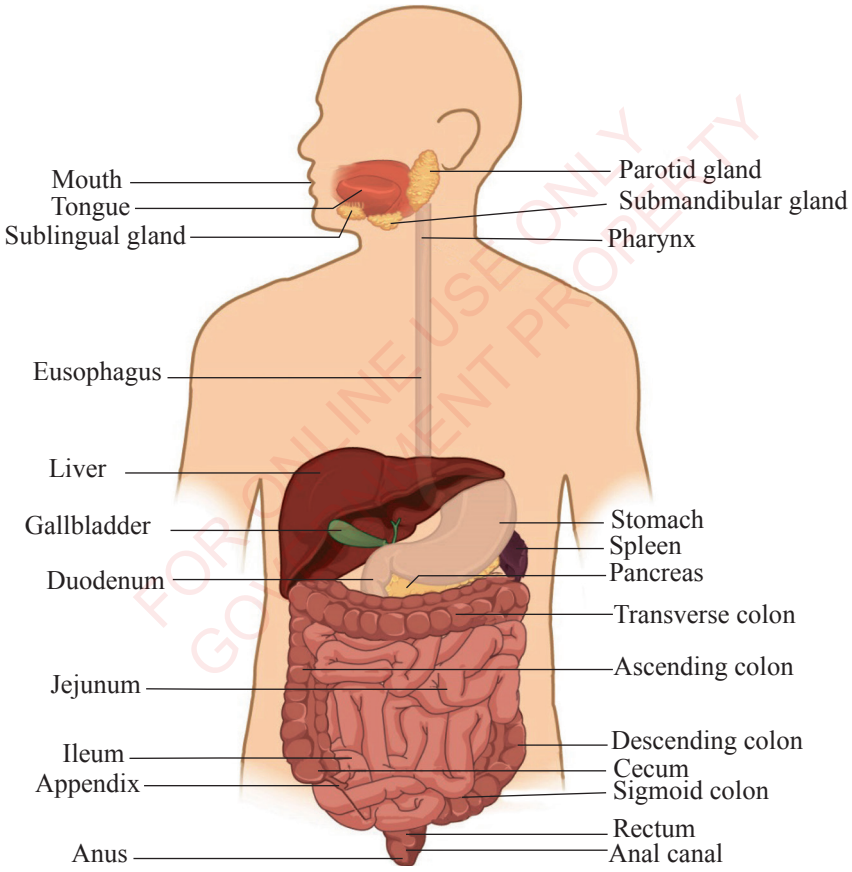


Figure 5.9 The human alimentary canal

Epithelial tissue

Epithelial tissue is a living tissue of various parts of the body. It consists of a single cell layer which usually occurs on the surface and covers the organs, cavities, and tubes. For instance, it lines the heart, blood vessels, lymphatic vessels, and the intestine within the organism. There are two major types of epithelial tissue; one is the simple epithelial tissue which has a single layer of tissue and is further subdivided into five sub types namely; squamous, cuboidal, columnar pseudostratified, ciliated, and glandular epithelial tissues. The second group of epithelial tissue comprises of epithelia tissues which have more than one cell thick. This group includes transitional and stratified epithelial tissues.

Columnar epithelium

This tissue consists of thin columns of elongated cells arranged at right angle to the basement membrane. The cells possess nuclei at their bases, and they are mostly associated with regions such as the walls of the intestines and stomach, where secretion and absorption are the major functions. Columnar epithelium tissues are adapted to withstand wear and tear. Epithelial tissue cells are interspaced by the goblet cells that are responsible for secreting mucus which helps to protect the stomach from digestive enzymes and acidic content of the gastric glands. Some epithelial tissues are ciliated while others have microvilli that increase the surface area for absorption. Part of the surface that is occupied by the microvilli is called brush boarder (Figure 5.10).

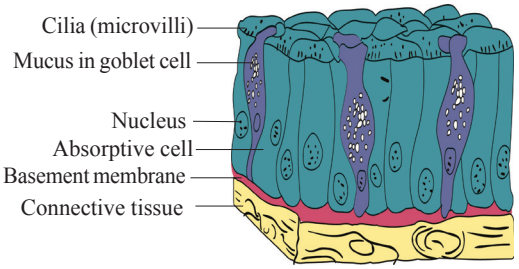


Figure 5.10 Simple columnar epithelium

Glandular epithelium

This epithelium tissue contains secretory cells that are closely packed (Figure 5.11). Secretory cells secrete materials such as mucus into the cavity or a space lined by it. For example, in the stomach and the small intestine the mucus protects and lubricates the lumen of the intestine and stomach. In some parts, glandular epithelium is folded in various ways to form glands such as gastric glands whose major function is to secrete enzymes and fluids. Glandular epithelium can be individual cells, such as goblet cells or aggregates of glandular cells, such as multicellular glands like exocrine and endocrine glands. Examples of glandular epithelial tissues found in the digestive system include simple tubular glands such as crypts of Lieberkuhn found in the intestines, simple branched tubular glands such as gastric glands found in the stomach walls (gastric mucosa), and compound saccular and compound tubular glands of the salivary glands.

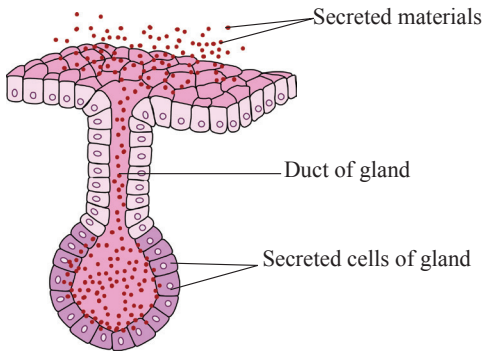


Figure 5.11 Glandular epithelium

Cuboidal epithelium

This tissue is made up of cells which are cube-like in shape with a central nucleus. They usually form a lining of the salivary glands where they perform secretory functions (Figure 5.12). In some cases the cell surface of this tissue is ciliated or flagellated.

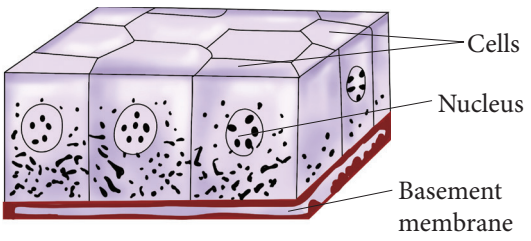


Figure 5.12 Cuboidal epithelium

Digestion in the mouth

Mechanical and chemical digestion of food starts in the mouth. Mechanical digestion is achieved by teeth through mastication (chewing). During mastication, the food is mixed with saliva, a watery mixture of mucus and amylase secreted by the salivary glands in response to thought, smell, taste or sight of food. Saliva is a neutral or very weak alkali with the pH ranging between 6.5 and 7.5. Saliva has the following functions with regard to digestion: it lubricates food so that it can move through the oesophagus easily; it catalyses the hydrolysis of starch into maltose using the enzyme called salivary α-amylase; It maintains pH of the mouth between 6.5 and 7.5. This level is optimum for the action of salivary amylase to function which is accomplished by its constituent mineral salts (example $NaHCO_3$).

Chemically, the digestion of food in the mouth involves converting starch into maltose by salivary α-amylase. The tongue which is located at the back of the buccal cavity rolls the food into a ball-like structure called bolus and forces it against the soft palate during swallowing, thereby closing the nasal cavity. The opening in the larynx (voice box) called glottis, is also closed by a flap like structure called epiglottis. Then, the bolus enters the oesophagus.

The oesophagus

In the oesophagus the bolus is moved by a series of wave-like movement caused by involuntary contraction and relaxation of its circular and longitudinal smooth muscles. This process is described as peristalsis. The contraction of circular muscles (inner muscles) causes the oesophagus to become narrow and long. The contraction of longitudinal muscles (outer muscles) causes the oesophagus to become wide and short. These contractions and relaxations of circular and longitudinal muscles push the bolus down the alimentary canal. Additionally, the peristalsis waves of contractions assist in mechanical digestion (Figure 5.13).

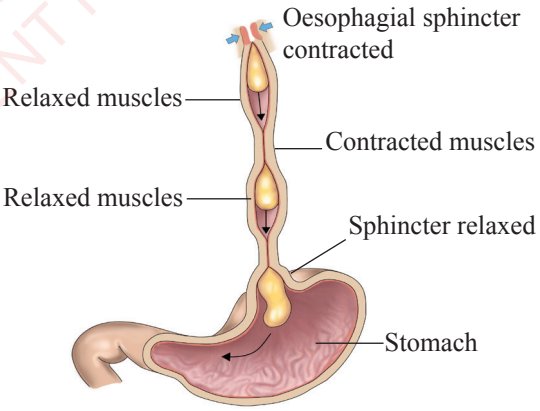


Figure 5.13 Wave of peristalsis in the oesophagus

The stomach

The stomach is a highly elastic muscular organ. It has two valve-like rings of smooth muscles called sphincters that can open and close. One sphincter is called cardiac sphincter. It is located between the oesophagus and the stomach. The second sphincter is called pyloric sphincter. It is positioned between the small intestine and the stomach. The stomach wall consists of a layer of mucous membrane called gastric mucosa, it is highly folded and is equipped with small pits (gastric pits) leading to gastric glands (Figure 5.14), in which gastric juice is secreted.

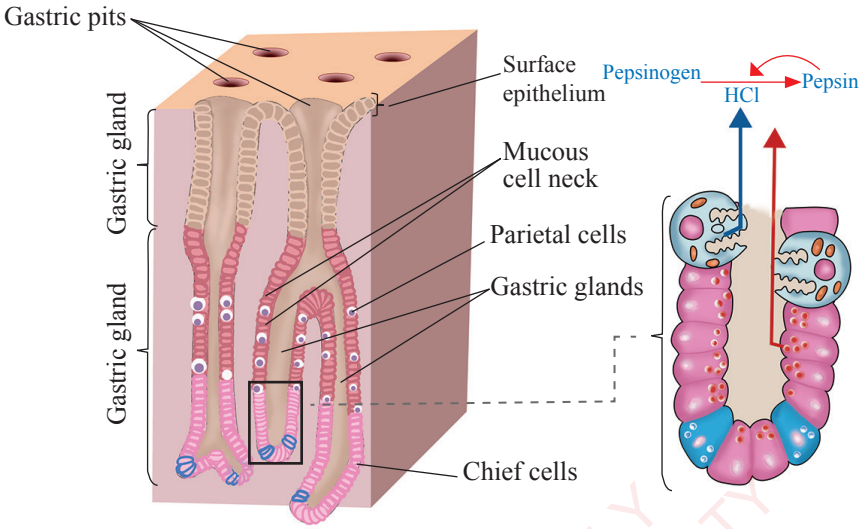


Figure 5.14 Structure of the gastric mucosa

Gastric juice has the following components:

Water. This is a solvent involved in hydrolysis by which food substances are broken down.

Hydrochloric acid (HCl). This is an acid produced by parietal cells of the gastric mucosa. Hydrochloric acid activates prorennin and pepsinogen into rennin and pepsin respectively, also kills any bacteria that might have entered the stomach through food.

Mucus. This protects the stomach from its own digestive enzymes and lubricates the wall for easy passage of food to the small intestine.

Pepsinogen. It is produced by the chief cells of the stomach wall. It is a precursor or inactive form of pepsin. Pepsinogen is activated by hydrochloric acid in the stomach to form pepsin; an enzyme responsible for the breaking down of polypeptides into peptides.

Prorennin: This is a precursor of rennin, the enzyme that catalyses the conversion of soluble milk protein into an insoluble milk protein. In other words, rennin is an important enzyme in coagulation or curdling of milk in the stomach. The coagulated milk is semi solid and it can be retained in the stomach for a relatively long time for proper digestion. This is very important in lactating young mammals.

In the stomach, mechanical digestion also occurs due to continuous contractions of the stomach wall which enhance breaking down of food mechanically. The combined action of mechanical and chemical digestion produces a creamy paste, an acid chyme. The formation of this chyme stimulates the receptors on the stomach wall, which in turn stimulates the pyloric sphincter muscles to relax and allow food to pass into the duodenum. Digestion of food in the stomach may take about 4 to 6 hours.

The intestines

The intestines are contained within the abdominal part of the body and they constitute the longest and the massive part of the alimentary canal. The word intestine comes from a Latin word meaning "gut or internal". The intestines are of two types namely; the small intestine which forms a vital part in the digestion and absorption of foods. The second type is the large intestine which among other functions is mainly important in re-absorption of water from the food residues before they are egested.

The small intestine

This part of the intestine has smaller diameter compared to that of the large intestine and for this reason it is called a small intestine. The diameter of the small intestine of human being is approximately 2.5 cm while the large intestine has a diameter of about 7.6 cm, which is about three times wider than the small intestine. The small intestine is the longest of all parts of the alimentary canal. It has the length of about 9 metres in a living person. The small intestine muscles are tight in the living body which makes it slightly shorter, unlike in a dead person where it becomes somewhat longer (about twice as much longer as its normal size in a living person). This is because death makes the small intestine to lose its muscle tone and stretches as it become loose. Unlike the large intestine, the small intestine has numerous folds and projections called villi on its lining which are important in increasing the surface area for digestion and absorption of food to take place. The surface area of the small intestine of a human is about 200 m^2 which is surprisingly closer to 100 times the surface area of our body skin. Schematically, the small intestine is normally surrounded by the large intestine in three sides.

The small intestine is not straight but rather a coiled tube which literally has three major distinct regions namely duodenum, jejunum, and ileum. The sectioning of the small intestine is based on its internal structure and function in digestion and absorption of foods.

Duodenum. This is the initial part of the small intestine immediately bordering with the pyloric sphincter of the stomach on the fore or proximal side and with the jejunum on the distal end. This part of the intestine is curved and it assumes a C-shape. The mid region of duodenum is an important part in which secretions from the pancreas and gall bladder together with intestinal wall secretions meet. The acidic chyme that enters the duodenum is subjected to chemical digestion by the secretions coming from the pancreas, intestinal wall, and the liver.

The liver produces a secretion called bile which is released into duodenum via the bile duct from the gall bladder. The bile contains bile salts such as sodium taurocholate and glycocholate which are responsible for emulsification of fats. Sodium bicarbonate has no digestive role, but rather it neutralises the acidic chyme from the stomach. The bile and pancreatic juice which flow into the duodenum are regulated by hepatopancreatic sphincter.

The pancreas is linked to the duodenum by a pancreatic duct. This exocrine gland produces various secretions which are collectively termed as pancreatic juice which contains the following components and their function in brackets: amylase (converts starch into maltose), trypsinogen (inactive form of trypsin which is converted into active form called trypsin by enterokinase). Others are trypsin (converts protein into smaller peptides), lipase (converts fats into fatty acids and glycerols), peptidase (converts peptides into amino acids), nucleases (convert nucleic acids into nucleotides), chymotrypsin (converts protein into small polypeptides), and sodium hydrogen carbonate (neutralizes the acid from the stomach).

Jejunum. This is the second region of the intestine and middle portion of small intestine measuring approximately between 2 and 3 meters long. This region stretches from the duodenum and connects it with the ileum. However there is no clear demarcation between jejunum and the ileum. It is responsible for nutrients absorption from the digested food to the blood stream with the aid of finger like structures known as villi. The absorbed materials are in form of mineral electrolytes, proteins, carbohydrates, and fats. These materials are utilized by the body.

Ileum. This is the final section of the small intestine in most of high vertebrates, including mammals, reptiles and birds. It is the longest region of the small intestine stretching from the distal portion of the jejunum through proximal portion of caecum of the large intestine at the ileocecal sphincter which is also known as a valve. In human being, it range between 2 and 4 metres long and pH ranging between 7 and 8 (neutral to slightly alkaline). In comparison to the other two parts of the small intestine ileum, is characteristically thicker; more vascularised and has more mucosal folds. Parasympathetic and sympathetic nerve fibres provide extrinsic innervations to the small intestine. The wall of ileum secretes intestinal juices (saccus entericus) which contain mucus, sodium hydrogen carbonate ($NaHCO_3$) and digestive enzymes. Mucus and sodium hydrogen carbonate are secreted by Brunner's glands, which are found in the interstitial wall. The role of mucus is to lubricate the interstitial wall and prevent corrosion, whereas sodium hydrogen carbonate helps to neutralise acidic chyme.

The digestive enzymes produced by the epithelial cells of interstitial wall include carbohydrase and proteases. Carbohydrase enzymes such as amylase converts remained starch into maltose, lactase converts lactose to galactose and glucose, and sucrase converts sucrose into fructose and glucose. Protease (erepsin) enzymes convert peptide into amino

acids. Additionally the ileum performs absorptive role as it absorbs vitamin B_{12}, bile salts and any other nutrients which are not absorbed in the jejunum.

The ileum as a site for absorption

Ileum is a site for digestion and absorption of digested food in the alimentary canal. The absorption is done through diffusion or active transport aided by various adaptive features including presence of circular folds, villi, and microvilli. These features increase the surface area for absorption of nutrients. Villi are finger-like projections on the intestinal wall which are equipped with smaller folds called microvilli on their surface. The surface occupied by microvilli is called a brush boarder. Folds are deep ridge like structures found on the mucosa and submucosa wall. These folds are important in disrupting the straight movement of food into meander-like movement which ultimately delays food movement in the ileum, thus availing more time for digestion and absorption to take place.

The villi are numerous hair-like projections found on the surface of the folds. The function of the villi is to increase the surface area of the intestinal epithelium for an effective absorption. Normally in 1 mm^2 there can be as many as 40 villi. Mucosal epithelium composed of absorptive cells which covers the villi. The villi are equipped with a large number of blood vessels that carry sugars, minerals, vitamins, and amino acids to the liver for processing. Each villus is supplied with venules, arterioles, capillaries and lymphatic capillaries. Moreover, there are lacteal vessels in the villi which are important for the transportation of fat soluble substances (fatty acids and glycerol) into lymph vessels.

The mucosa between the folds contains deep tissues lined by cells that lead to a tubular intestinal gland called crypt of Lieberkühn. This gland secretes slightly alkaline juice which is triggered by irritation on the mucosa caused by acidic chyme.

Microvilli are cylindrical extensions of the epithelial mucosa cells. They are much smaller than the villi, measuring about 1µm. Due to their small size, a mass of microvilli appears as fine bristle brush called brush borders. The surface of microvilli contains enzymes which accomplish digestion of proteins and carbohydrates. The brush borders increase the surface area of the membrane plasma to increase absorption. Microvilli increase the surface area for absorption (Figure 5.15). The surface of the villus is lined with the epithelial cells having large number of mitochondria to provide energy for active transport of nutrients, such as amino acids and glucose which are taken against their concentration gradient.

These nutrient-rich blood from the small intestine are carried to the liver via the hepatic portal vein. Presence of longitudinal and circular muscles in the villus enhances contraction and relaxation which brings villus into contact with the food.

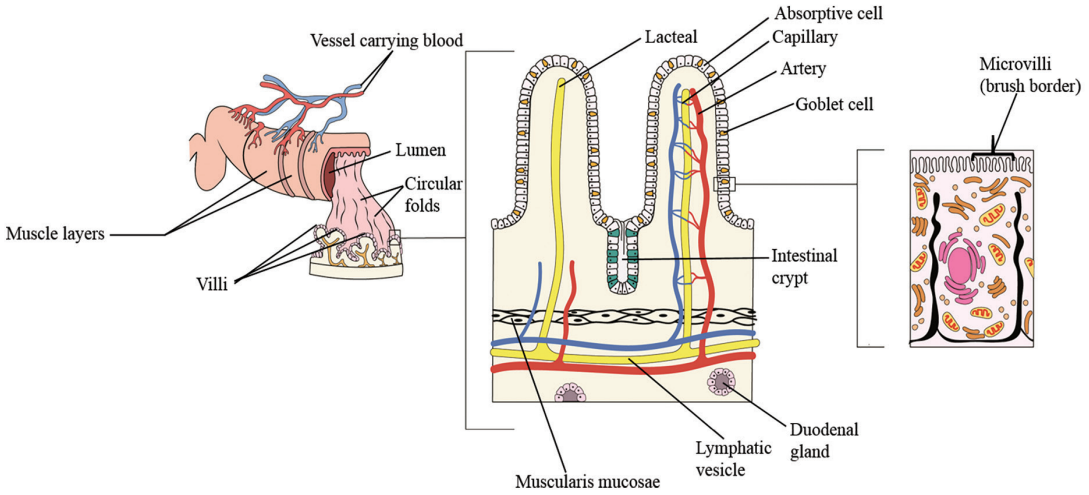


Figure 5.15 Transverse section of a small intestine

The large intestine

This is the last part of the alimentary canal that extends from a blind pouch called caecum through anus. It surrounds the small intestine in three sides. This type of the intestine is involved in the final stage of water absorption, synthesis of certain vitamins, formation and expulsion of faeces to outside the body. The region between the ileum and caecum has a sphincter known as ileocaecal sphincter and it is responsible for the movement of undigested food materials from the ileum to the large intestine.

The large intestine differs in many ways from the small intestine as explained earlier. Besides its diameter, which is relatively larger than that of small intestine; it has a few enzymes secreting cells in its walls. The villi which are numerous in the small intestine are missing in the large intestine. The wall of the large intestine is thus simple in structure and has simple columnar epithelium. The intestinal mucus secreting glands are relatively more in number than they are in the small intestine. The mucus in the large intestine is important in lubricating the food residues moving out as faeces while also protecting the intestine from effects of acids and gases produced by enteric bacteria. The large intestine therefore, had four major regions, namely: caecum, colon, rectum and anus.

Caecum. This is a sac-like structure of about 6 cm suspended interior to the ileocecal valve. Undigested food materials from the ileum are first received by this region of the large intestine where absorption of water and salts is continued. In this region a winding tube called appendix is attached and its function is not clearly known hence it is considered as a vestigial organ. However, appendix is reported to have immunological function because it contains a group of white blood cells. Recent studies have also shown appendix to have bacteria reservoir which are important in repopulating the enteric bacteria in the early stages of individuals

suffering diarrheal illness. As the faeces pass along the large intestine, some water is absorbed into the blood stream.

Colon. This region of the intestine borders with caecum and it is made up of four sub regions namely the ascending, transverse, descending and sigmoid regions. Food residues from caecum enter the ascending region of the colon first which is on the right side of abdomen and travel up through the first bend of the colon to the transverse region of the colon. The residue continues through the second bend to the descending colon which is on the left side of the posterior abdominal wall and enters the sigmoid colon.

Generally, colon is very important in the water balance of the body. Every day, about seven litres of water from drinks and watery secretions produced internally, enter the gut. If most of these were not reabsorbed, it could lead to dehydration of the body. Thus, re-absorption of water in the large intestine is necessary to prevent water loss.

Rectum. After food residues have passed through the sigmoid colon, the remaining intestinal content is stored as faeces in the rectum which measures about 20 cm long. Rectum is located interior to the pelvis and it produces some mucus materialwhich are added to the faeces in order to lubricate it for easy passage to the outside by the process called defecation. The desire for defecation is caused by the presence of a large quantity of faeces in the rectum. The walls of the rectum have curved contours and lateral bends which create internal transverse folds called rectal valves. The function of these valves is to separate faeces from gas in order to prevent simultaneous passage of faeces and gas.

Anus. This region is also called anal canal and constitutes the final part of the large intestine. The length of the anal canal is between 3.8 to 5 cm and it opens to the exterior of the body at the anus. It has two types of muscles; the internal anal sphincter and external anal sphincter. The former first type of muscle is made up of smooth muscles, and its contractions are involuntary, while the later is made up of skeletal muscles and they are under voluntary control. Under normal conditions, these two types of muscles make the sphincter remain closed except when defaecating.

Nervous and hormonal control of the gastric juice secretion

Digestion is vital for the functions of all systems of a human body. It is under the nervous and hormonal control systems. Until 19^{th} century, biologists regarded the digestive system as being entirely under nervous control. However, in 1902 a British physiologist Sir William M. Baylyss discovered secretin hormone as vital in the control of gastrointestinal functions. Three types of hormones involved in digestion are secretin, gastrin and cholecystokinin. Secretion and release of these hormones is stimulated by presence of certain food molecules in the stomach and small intestine.

Digestion process is controlled by two types of nervous system namely; the somatic nervous system and the autonomic nervous system. The somatic nervous system enables the body to adapt to stimuli such as touch and smell from the external environment and is the system that controls the gastrointestinal tract. This somatic nervous system is further divided into sympathetic and parasympathetic nervous systems. Stimulation of sympathetic system brings about shunting of blood from gastrointestinal tract. This reduces digestive activity and causes dry mouth and cessation of salivation.

The parasympathetic nervous system, on the contrary, is responsible for the secretion of saliva, production of digestive enzymes, activation of digestion process and increased peristalsis. The parasympathetic system dilates blood vessels to increase blood flow to the gastrointestinal tract after the consumption of food, due to great or high metabolic demand placed on the body by the gut. The control of gastric juice secretion occurs in three phases, namely, nervous, gastric, and intestinal phases. The mechanisms of the nervous and hormonal control of digestion phasewise is as detailed here under.

The nervous or cephalic phase. This is the initial stage which is initiated by sight, thought, taste, or smell of food, which later triggers a reflex in which nerve impulses relayed from the brain cause gastric glands to release their secretions. Generally, the nervous signals that trigger this phase emanate from cerebral cortex appetite centres and are transmitted to the stomach through the vagus nerve. This in turn causes the secretions of histamine and increases hydrochloric acid and gastrin secretion in the stomach. In comparison to other phases, the cephalic phase contributes about 20% of the gastric secretions while eating.

Gastric phase. This is the second phase and it is so called because it triggers gastric activity. It occurs once the food is chewed and has arrived in the stomach. The partially digested food substances such as proteins in the stomach stimulate the endocrine cells in the stomach walls to secrete gastrin from gastric glands which increase the secretion of the gastric juice.

Normally, the ingested food stimulates gastric activity by stretching the stomach and raising pH of its contents. Stretching activates the short and long reflexes that lead into the production of acetylcholine secreted by the parasympathetic nerve fibres. The acetylcholine and histamine from the gastric glands together with gastrin stimulate parietal cells to secrete hydrochloric acid. The chief cells secrete pepsinogen in response to gastrin secretion. Digestion of protein into peptides and amino acids, stimulate gastrin cells directly to secrete more gastrin to accelerate further protein digestion. Normally, peptides buffer the stomach acidity; therefore, as they leave the stomach acidity increases and as pH gets below 2, a negative feedback is triggered to inhibit the parietal and gastrin cells. This process winds up the gastric phase as the need for pepsin and HCl declines. Furthermore, when fat-containing food enters the stomach, the hormone called enterogastrone or gastric inhibitory peptide is released from the wall of the stomach. This hormone decreases the flow

of gastric juice and reduces movement of the muscles of the stomach (churning motions) or gastric peristalsis.

Intestinal phase. This phase occurs when chyme arrives in the first region of the small intestine called duodenum and triggers gastric activity and nervous reflexes. Food material in the duodenum stimulates both the alkaline and enzyme-rich components of pancreatic juice. The alkaline component of pancreatic juice is secreted in response to the presence of acid in the duodenum. The acidified chyme in the duodenum triggers the secretion of secretin and cholecystokinin (CCK) or pancreozymin (PZ) from the duodenal walls. Secretin causes the production of bile and mineral salts from gall bladder and pancreas respectively. CCK stimulates the secretion of enzymes from pancreas and contraction of gall bladder to release bile. Moreover, secretin and CCK suppress gastric secretion and motility in which a decline in gastrin secretion and contraction of pyloric sphincter will limit admission of more chyme into the duodenum. This gives the duodenum ample time to work on the chyme it has received before receiving more. The enteroendocrine cells also secrete gastric-inhibitory peptide, also called gastrointestinal inhibitory peptide (GIP) which inhibits the secretion of gastric acid in the stomach. Also GIP stimulates insulin secretion in preparation for processing nutrients that are about to be absorbed by the small intestine. Trypsin in the duodenum inhibits the release of enzymes via the inhibition of CCK.This is a feedback control mechanism which limits the quantity of enzymes in the small intestine and may have a protective function.

Exercise 5.5

1. Describe the structure of epithelial tissue of the digestive system.
2. Explain how glandular tissues of the alimentary canal are adapted to the functions they perform.
3. a) Describe the functions of the mammalian stomach.

   b) Explain why surgical removal of the stomach in human is not necessarily fatal.
4. Describe the role of the liver in digestion.

Revision questions

1. Distinguish between autotrophic and heterotrophic modes of nutrition.
2. Photosynthesis is not possible without photolysis of water. Explain.
3. Explain the role of RuBP and NADPH in photosynthesis.
4. Differentiate between cyclic and non-cyclic photophosphorylation.
5. Describe the mechanism of Hatch-Slack in C_4 plants.
6. Using vivid examples, explain types of heterotrophic nutrition.
7. Explain the role of the pancreas in digestion.
8. Explain the process of digestion in human alimentary canal.
9. Bile does not contain enzyme, yet it is important for digestion. Explain.
10. Give an account on the nervous and hormonal control of the gastric juice secretion.
11. Explain the factors that affect the rate of photosynthesis.

Chapter
Six

Gaseous exchange and respiration

Introduction

All living organisms exchange gases between their respiratory surfaces and the surrounding environment. Respiration is an energy yielding process that liberates energy, which is used by living organisms to perform various body activities. It is a vital process to all living organisms as it provides energy for all metabolic processes. In this chapter, you will learn about the mechanisms of gaseous exchange in mammals and plants and the process of respiration.

6.1 Gaseous exchange in mammals

Gaseous exchange entails a process of exchanging respiratory gases between the cell of an organism and its environment. Oxygen is required for aerobic respiration. All organisms that undergo aerobic respiration obtain oxygen from their environment and carbon dioxide, a waste product of respiration is returned to the environment. The area for gaseous exchange within the organism's body is called respiratory surface. The process of gaseous exchange takes place by diffusion. In mammals and other animals, the principal organ for gaseous exchange is the lung(s).

The internal structure of the mammalian lung

A pair of lungs is situated in the thoracic cavity together with the heart. The cavity has a protective bony cage called the rib cage. The rib cage has ribs and intercostal muscles that allow its movements during exhalation and inhalation of air. It is surrounded by a double pleural membrane between which pleural fluid is found. The fluid aids as a lubricant, preventing abrasion of the lungs during breathing. It is also associated with the muscular sheath known as the diaphragm. The diaphragm separates the thorax from the abdomen. During inhalation the volume of the thoracic cavity increases, thus lowering pressure. This is caused by the downward movement of the diaphragm and the outward movement of the ribs. During exhalation, the volume of the thoracic cavity decreases, thus raising the pressure. This is caused by the upward

movement of the diaphragm and inward movement of the ribs.

The lungs consist of the trachea, bronchi, bronchioles, alveolar ducts, alveolar sacs and alveoli (Figure 6.1). The alveoli are the main functional units of the lungs. Trachea is the windpipe that connects the larynx and the bronchi. It receives air from the nostrils through the nasal cavity. In the latter, the air is warmed and cleared from dust and germs that may have entered the cavity with it. The nasal cavity possesses hairs which help to trap dusts and other tiny particles. The trachea has cartilages in its walls that keep it firm and intact. It is associated with ciliated epithelium and goblet cells. The cilia beating moves the trapped dusts and bacteria back to the cavity where they get swallowed. The goblet cells are essential for mucus production that traps dusts and bacteria altogether. It also moistens the air that passes down to the alveoli. The trachea branches at its lower end into two bronchi. Like the trachea, each bronchus has cartilage and ciliated epithelium with goblet cells which play a role of trapping dust and bacteria. Each bronchus subdivides into many smaller tubes known as bronchioles. They have cartilage, cilia, and the goblet cells that work similarly as in the trachea and bronchi; they trap foreign substances. The bronchioles branch into very fine tubes, alveolar ducts, ending into alveolar sacs and each alveolar sac opens into a group of alveoli. The alveolar ducts, alveolar sacs, and alveoli do not possess cartilage, cilia and goblet cells. The alveolus possesses features that allow it to function in a special way compared to other structural parts of the lungs.

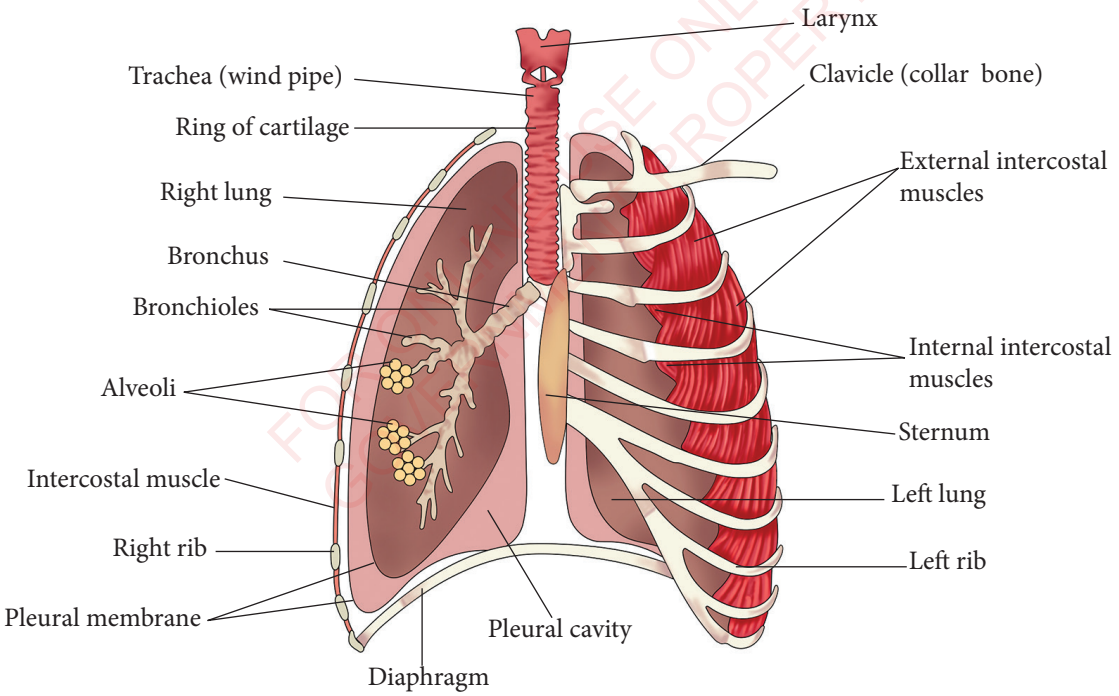


Figure 6.1 Structure of the mammalian lungs

Alveolus

The alveolus is a tiny air-filled sac of the mammalian lung. Gaseous exchange takes place in the alveolus and actually, it is a functional unit of the lungs. The estimated total amount of the alveoli in the average human is about 700 million that has a total surface area of over 80 square metres which facilitate the rate of gaseous exchange. The alveoli are thin, moist and are well supplied with a dense capillary networks, hence they are highly adapted for efficient gaseous exchange. In the process of gaseous exchange, oxygen gas from the alveoli diffuse quickly across the alveolar wall through the air-blood barrier into the blood capillaries and carried to the heart through pulmonary vein. On the other hand, the carbon dioxide from the body tissues enters the heart and carried from the heart to the lungs by the pulmonary artery. It diffuses through the blood capillary to the alveoli and is then exhaled (Figure 6.2).

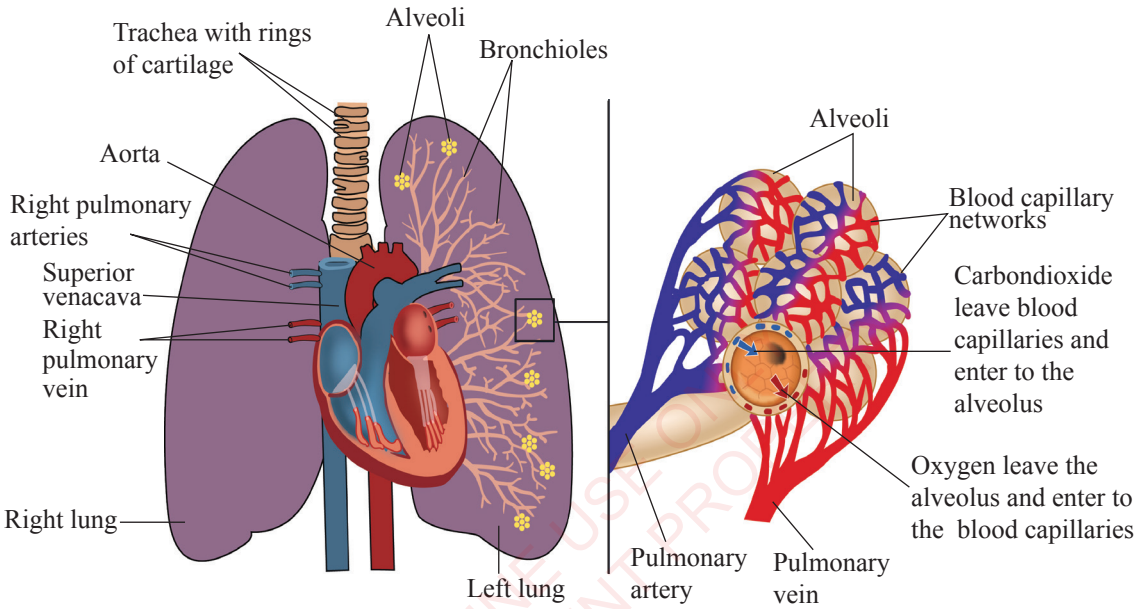


Figure 6.2 Structure of the mammalian lungs showing the association between alveoli and blood vessels during gaseous exchange

Structurally, the alveoli possess connective tissues with elastic collagen fibres that allow them to expand and recoil during breathing. Alveoli have special epithelia cells in their walls that secrete a detergent-like chemical known as surfactant into the alveolar space. The surfactant lowers the surface tension of the fluid inside the alveoli, hence reducing the energy required to breathe in and inflate the lungs. It also kills bacteria trapped in the incoming air through the nostrils. In addition, it increases the rate of gaseous exchange in mammals. They also have macrophages which are protective cells that remove debris and microbes by phagocytosis (Figure 6.3).

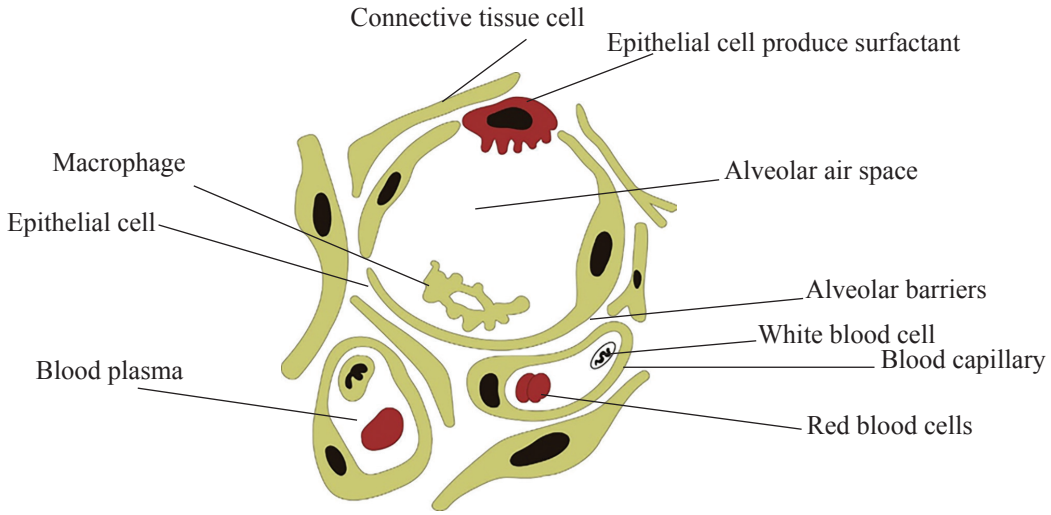


Figure 6.3 Structure of the alveolus

Surface tension of the lungs

The surface tension provided by surfactant stabilizes the alveoli during inflation and dilation resulting from inhalation and exhalation of gases. The surfactant is a phospholipid and a protein chemical produced in early development stage of foetus. This chemical helps to lower the surface tension and promote lungs' expansion during inspiration (inhalation) and preventing alveolar collapse. It is also believed to protect the lungs from infections.

The proteins and lipids that make up the surfactant have both hydrophobic and hydrophilic region that are important in lowering the surface tension by adsorbing to the air–water surface interface, with hydrophobic head groups in water and hydrophobic tail facing towards the air.

Activity 6.1 Observation of the structure of the mammalian lungs

Materials

Mouse or rat, dissection kit, dissecting tray, chloroform, and cotton wool.

Procedure

a) Use your dissection knowledge to open up the body cavity of a mouse in the usual way to display the lungs.
b) Use a hand lens to observe the thoracic and abdominal cavities as well as the diaphragm.

Questions

1. Draw a well labelled diagram of your dissection.
2. Explain the functions of each part of the mammalian lungs.

Safety precautions

1. Laboratory rules and regulations should be adhered to.
2. Rat or mouse may bite and also their fur may cause allergy to a human being.

Factors governing gaseous exchange at respiratory surface

Gaseous exchange occurs on the respiratory surface; a boundary between the external environment and the interior of the body of an organism. Mammalian respiratory surface consists of many air sacs called alveoli which are found inside a pair of lungs. An efficient gaseous exchange occurs when the respiratory surface has large surface area and can quickly distribute and collect gases throughout the body. Moreover, an efficient gaseous exchange can occur when the respiratory surface has ability to speed up or slow down the exchange rate to meet the body demand. In general, for an efficient gaseous exchange in mammals, the respiratory surface must have the following features:

a) Large surface area of the membrane

There is a direct relationship between the surface area and the rate of gaseous exchange. Generally, the larger the surface area of the membrane, the higher the rate of gaseous exchange. This is because when the surface area is large, more blood and air can circulate, hence increasing the rate of gaseous exchange.

b) Concentration gradient

Concentration gradient is created when the two sides separated by a membrane have different concentrations of gases. This difference in concentration is actually what facilitates the process of gaseous exchange because gases can move from areas of high concentration to those of low concentration. Therefore, for gaseous exchange to occur there must be a concentration gradient.

c) Availability of high supply of blood capillaries

The mammalian respiratory surfaces are well supplied with blood by blood capillaries. This enables high uptake of oxygen in the alveoli, which increases the rate of gaseous exchange. In the red blood cells, there is haemoglobin that helps to transport oxygen by combining with it to form oxyhaemoglobin which helps in transportation of oxygen to different parts of the body where it is required.

d) Thickness of the membrane

The rate of gaseous exchange is affected by the thickness of the membrane across which the gases have to diffuse. A thick membrane reduces the rate at which gases diffuse from areas of high concentration to those of low concentration. This is due to long distance of travel as the result of membrane thickness. Generally, the thickness of the membrane is inversely proportional to the rate of diffusion.

e) Diffusion distance

The distance across which air, blood, or plasma fluid has to diffuse also determines the rate of gaseous exchange. In single-celled organisms, gaseous exchange tends to be faster because the gases have to diffuse through only one cell surface membrane while in multi-cellular organisms, gaseous exchange requires a complex transportation and respiratory system as the gases are transported through a longer distance.

f) Moist surface

Since respiratory gases are transported in solution form, they must dissolve in liquid before they are carried away from

the respiratory surfaces. Thus, an efficient respiratory surface must be moist for rapid exchange and transportation of respiratory gases.

g) Permeability

Since the membrane form the boundary between organism and its extracellular environment, its permeability affects the rate of gaseous exchange. Therefore, a respiratory surface must be permeable to allow gases to pass through.

Oxygen and carbon dioxide transport in vertebrates

Oxygen and carbon dioxide are the respiratory gases that have to be transported from one part of the body to another. Oxygen is transported from the respiratory surfaces to the respiring body tissues and carbon dioxide has to be transported from the respiring body tissues to the respiratory surfaces. Vertebrates such as mammals, birds, reptiles, amphibians and fish, have a variety of respiratory surfaces, ranging from gills in fish and tadpoles to lungs in adult amphibians, reptiles and mammals.

Oxygen transport in vertebrates

In vertebrates oxygen is transported in two ways: as dissolved oxygen in blood plasma and by means of red blood cells. The oxygen transported in solution form in the blood plasma accounts for only about two percent (2%), and the remaining ninty eight percent (98%) is transported by the red blood cells. The red blood cells have a red pigment called haemoglobin which is responsible for transport of oxygen and carbon dioxide in the blood. Structurally, the haemoglobin molecule consists of four Iron-containing parts and four protein chains. Each haemoglobin molecule binds to four oxygen molecules, forming the oxyhaemoglobin molecule. This is carried to individual cells in the body tissue where it is released. The binding or combination of oxygen and haemoglobin is a reversible process as shown in the equation below:

$$\underset{\text{Haemoglobin}}{Hb} + \underset{\text{Oxygen}}{4O_2} \underset{\text{Low } [O_2]}{\overset{\text{High } [O_2]}{\rightleftharpoons}} \underset{\text{Oxyhaemoglobin}}{Hb.4O_2}$$

According to the above equation, at high oxygen concentration, oxyhaemoglobin is formed, whereas at low oxygen concentration, oxyhaemoglobin dissociates into haemoglobin and oxygen. This dissociation releases oxygen from haemoglobin. The balance can be shown by an oxygen dissociation curve of oxyhaemoglobin (Figure 6.4). In the oxygen dissociation curve, the greater the concentration or partial pressure of oxygen, the more saturated with oxygen the haemoglobin becomes. Usually the graph is S-shaped or sigmoid.

The curve shows the following:

a) At relatively low oxygen concentration, there is uncombined haemoglobin in the blood and little or no oxyhaemoglobin exists. This is most likely to occur in the body tissues, where oxygen concentration is likely be low.

b) At relatively high oxygen concentration, haemoglobin combines with oxygen

in the blood to form oxyhaemoglobin. Therefore, most haemoglobin molecules are saturated with oxygen. This situation is likely to occur in the lungs, where oxygen concentration is high.

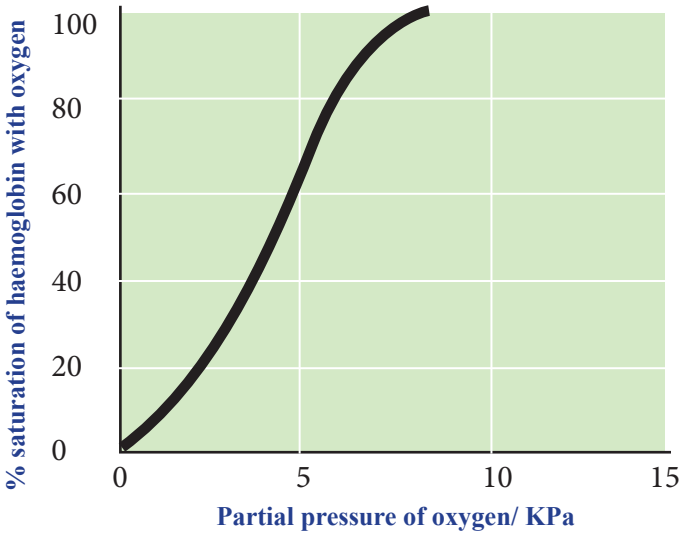


Figure 6.4 The oxygen dissociation curve of haemoglobin

The effect of carbon dioxide in the transport of oxygen in blood

Increased concentration of carbon dioxide can affect oxygen transport in the blood. This is because haemoglobin can combine with carbon dioxide (although to a lesser extent) to form carbaminohaemoglobin. The presence of carbon dioxide lowers the affinity of haemoglobin to oxygen and causes the release of oxygen from haemoglobin. Therefore, an increase in carbon dioxide in the tissues causes faster release of oxygen from haemoglobin and this is known as the Bohr Effect which is the result of shifting of dissociation curves to the right in areas with increased partial pressure of carbon dioxide (Figure 6.5). The effect of carbon dioxide concentration on oxygen transport by haemoglobin can be revealed by comparing the oxygen dissociation curves when less carbon dioxide is present and when more carbon dioxide is present in the blood.

The Bohr Effect

The Bohr Effect is an increase in carbon dioxide partial pressure of the blood or decrease in blood pH resulting into a lower affinity of haemoglobin to oxygen. It is manifested by right-ward shifting of oxygen dissociation curve, resulting from enhanced unloading of oxygen by haemoglobin. The relationship between carbon dioxide partial pressure and blood pH is mediated by carbonic anhydrase which catalyses conversion of gaseous carbon dioxide to carbonic acid, that in turn releases a free hydrogen ion, hence reducing the local pH of blood.

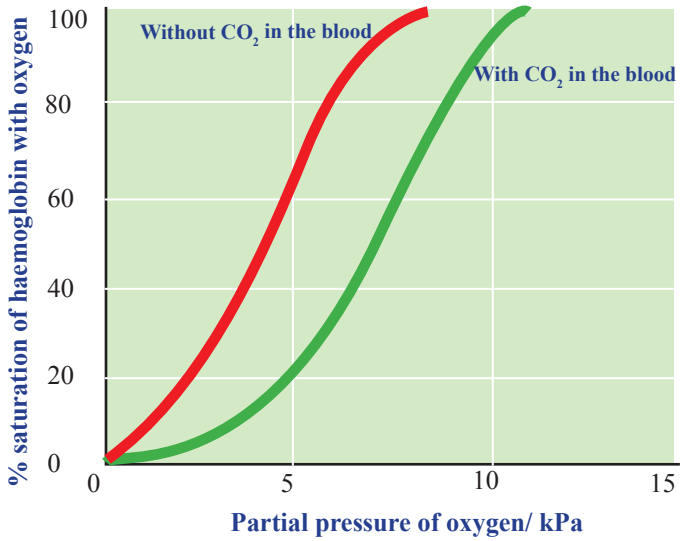


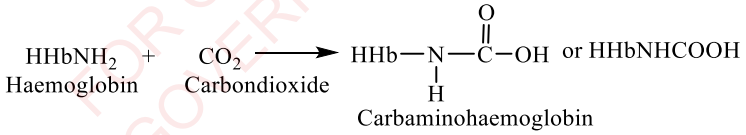
Figure 6.5 Oxygen dissociation curves of haemoglobin at different partial pressures of carbon dioxide

Transport of carbon dioxide

Carbon dioxide diffuses out of the tissues into the blood for transportation. The body does not allow accumulation of carbon dioxide because it forms an acid with water that could lead to fatal changes of blood pH. Carbon dioxide is transported both, in plasma and in red blood cells by three different ways.

a) It can be transported either as physical solution (as dissolved carbon dioxide) or as carbonic acid (H_2CO_3). However it is only about five percent (5%) of carbon dioxide that is transported in solution form and a small amount as carbonic acid.

b) It can be transported in combination with proteins: carbon dioxide combines reversibly with haemoglobin to form a compound known as carbaminohaemoglobin. It does not bind to iron as oxygen does but to amine group (NH_2) at the end of each polypeptide chain of haemoglobin and plasma proteins. About 10 – 20% of carbon dioxide is transported in this way.



c) It can be transported as hydrogen bicarbonate ions (HCO_3^-). Most of the carbon dioxide (about 85%) in the body is transported as hydrogen carbonate. Carbon dioxide enters red blood cells in the tissue's capillaries where it combines with water to form carbonic acid (H_2CO_3). This reaction is catalysed by the enzyme carbonic anhydrase which is found in red blood cells. Then, the carbonic acid dissociates to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+).

$$\underset{\text{Carbondioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \xrightleftharpoons{\text{Carbonic anhydrase}} \underset{\text{Carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{Bicarbonate ion}}{HCO_3^-} + \underset{\text{Hydrogen ion}}{H^+}$$

Most of the hydrogen carbonate ions formed in the red blood cells diffuse from the cytoplasm to the plasma and combine with sodium to form sodium hydrogen carbonate. The negatively charged hydrogen carbonate ions are lost from the blood cells, leaving them with a more positive charge. This is balanced by diffusion of chloride ions (Cl^-) in the opposite direction, maintaining the balance of negative and positive ions in either side of the plasma and red blood cells. This is called the chloride shift which is also known as the Hamburger shift or Hamburger phenomenon. It is named after the founder, Hartog Jakob Hamburger. The chloride shift reaction occurs in the respiring cell. When the red blood cells reach the lungs the reverse process or reaction occurs and carbon dioxide is released (Figure 6.6).

The dissociation of carbonic acid increases the acidity of the blood. Hydrogen ions (H^+) then react with oxyhaemoglobin to release bound oxygen and reduce the acidity of the blood. This buffering action allows large quantities of carbonic acid to be carried in the blood without major changes in blood pH.

$$Hb.4O_2 + H^+ \rightleftharpoons HHb^+ + 4O_2$$

This reversible reaction accounts for the Bohr Effect. Carbon dioxide is a waste product of respiration. Its concentration is high in the respiring cells; it is here where the haemoglobin releases oxygen.

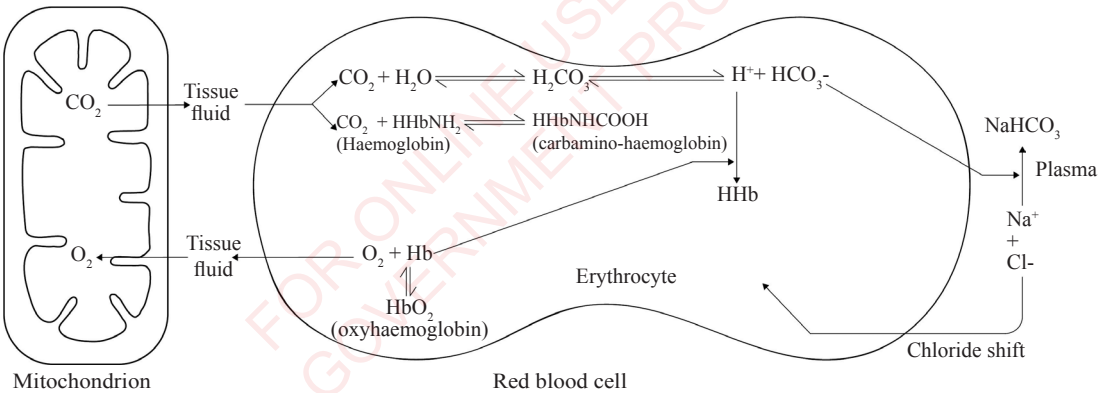


Figure 6.6 Carbon dioxide transport by plasma and red blood cells

Haemoglobin is strongly attracted to carbon dioxide molecules. Carbon dioxide is removed to reduce its concentration in the cell and is transported to the lungs where its concentration is low. This process is continuous since oxygen concentration in the lungs, is always higher than that of carbon dioxide, while in the respiring cells carbon dioxide concentration is always higher than that of oxygen.

Adaptation of organisms to oxygen uptake

The percentage of oxygen in the air does not change significantly at different altitudes, but the atmospheric pressure falls with increasing altitudes. The oxygen tension (partial pressure of oxygen molecules dissolved in blood plasma) varies with altitudes (Table 6.1). Organisms living in a particular altitude have to develop adaptive features that can enable them to sustain their lives in their particular environment. Among the organisms that live in the environments that need them to develop some adaptive features aimed at facilitating oxygen uptake include mountain dwellers, divers, and mammalian foetus.

Table 6.1 The effects of altitude on the atmospheric pressure and oxygen tension

Altitude(m)above sea level	Atmospheric pressure(kPa)	Oxygen content(%)	Oxygen tension(kPa)
0	101.3	20.9	21.2
2500	74.7	20.9	15.7
5000	54.0	20.9	11.3
7000	38.5	20.9	8.1
10000	26.4	20.9	5.5

Adaptations to oxygen uptake for mountain climbers and dwellers

In mountain climbers and high altitude dwelling mammals, the rate of metabolism is high in order to ensure constant generation of enough energy to cope with climbing activities, hence the supply of oxygen should be assured. However, the partial pressure of oxygen in high altitude is low which makes the climbers difficult to pick up oxygen. For these reasons, mountain climbers and mammals living in high altitudes develop the following adaptive features:

a) Their bone marrow produce more red blood cells in order to raise the oxygen-carrying capacity of the blood.

b) They possess a form of haemoglobin with higher affinity to oxygen. This allows loading of oxygen by haemoglobin even at low oxygen tension.

c) They secrete more alkaline urine that normalises blood pH. The chemoreceptors become sensitive to carbon dioxide concentration and normal ventilation rates are maintained.

d) Their tissues are tolerant to high levels of lactic acid due to oxygen deficiency.

e) They have larger lungs, hence increased lung volumes and total lung capacity, therefore large amount of haemoglobin loaded with oxygen.

f) They have deep and slow breathing rate that improves ventilation efficiency for oxygen, since blood oxygenation increases, and it reduces systemic and pulmonary blood pressures.

Adaptations to oxygen uptake for divers

Divers in the deep water do not depend on lungs as a source of oxygen; instead, they rely on enhanced oxygen stored in their blood and muscles. Collapse of the lungs forces air away from the alveoli, where gaseous exchange between the lungs and blood occurs. This blunting of gaseous exchange is important in the deep diver because it prevents the absorption of nitrogen into the blood and the subsequent development of high blood nitrogen levels. High blood nitrogen pressure can exert a narcotic effect (so-called nitrogen narcosis) on the diver. It may also lead to nitrogen bubble formation during ascent, a phenomenon known as decompression sickness or "the bends". Collapse of the lungs in deep divers helps to avoid these two problems. Thus, diving mammals, besides the collapse of their lungs, have the following adaptive mechanisms to oxygen uptake:

a) They use oxygen more efficiently, that is, they fill their lungs and exchange 90% of their air in each breath. Thus, before a dive is taken, they take a deep breath to accumulate oxygen in their lungs.

b) They have a high blood volume with plenty of haemoglobin and myoglobin. This allows long oxygen retention time.

c) They have a high tolerance to lactic acid and carbon dioxide, that is, their muscles can work anaerobically while holding their breath.

d) They can tolerate tremendous atmospheric pressure at great depths. Their lungs and ribs are collapsible; air spaces are minimised; and nitrogen absorption is limited.

e) Diving mammals slow their heart rate, stop their breathing, and shunt blood flow from their extremities to the brain, heart, and muscles when starting a dive.

f) Seals can hold their breath for about two hours. They rely on internal oxygen stores when they are down there.

g) Myoglobin of the seals and dolphins is more concentrated than that of humans, almost ten times, this gives them a chance of storing oxygen for a long time when under water.

Adaptations of the mammalian foetus to oxygen uptake

The foetus lives and develops inside the maternal womb (uterus). It obtains nutrients, exchange gases and waste products with the maternal blood via the placenta. For the foetus to obtain oxygen from maternal blood, the oxygen has to diffuse from maternal blood to foetus blood. There are some adaptations to this, which are;

a) Foetal haemoglobin has higher affinity to oxygen; hence it can readily combine with oxygen to form oxyhaemoglobin

(Figure.6.7). This allows the foetus to extract oxygen from the maternal blood supply. In adult hemoglobin, the protein subunits are identical beta-chain subunits, while in foetal hemoglobin, the two subunits are identical gamma subunits. This change in structure of foetal hemoglobin also leads to a change in function when compared to adult hemoglobin. It has been shown that the structural changes in foetal hemoglobin caused by the substitution of gamma subunits for beta-chains, allows foetal hemoglobin to have a higher affinity to oxygen.

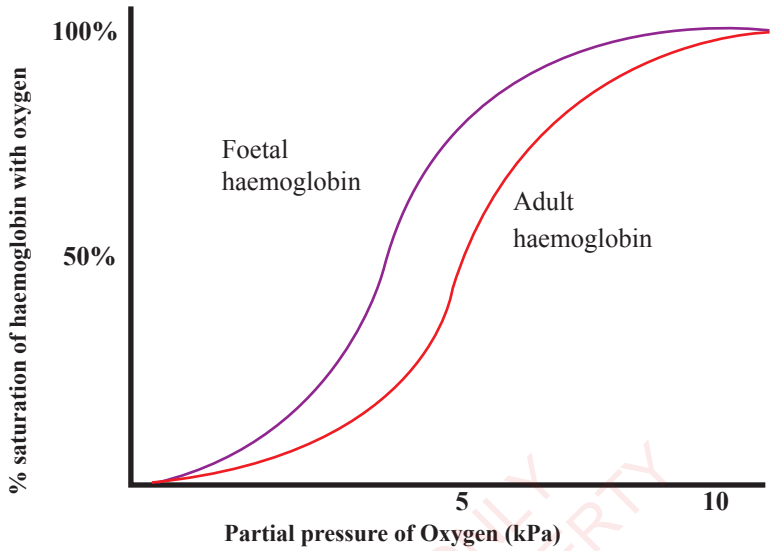


Figure 6.7 Oxygen dissociation curve for foetal and adult haemoglobin

b) There is increased intake of oxygen by maternal blood due to increased haemoglobin so as to ensure a large supply of oxygen to the foetus blood.

c) The uterine wall is highly vascularised (provided with blood vessels) to ensure continuous supply of oxygen to the foetus, as a result, the foetus loads its haemoglobin with oxygen efficiently.

Exercise 6.1

1. Explain why babies can stay alive in the wombs of their mothers despite the fact that they are not in direct contact with the atmospheric air.
2. Describe the ways by which oxygen and carbon dioxide are transported in vertebrates.
3. Draw the oxygen-haemoglobin dissociation curve and comment on its shape.
4. What is chloride shift? Explain how it occurs.

6.2 Gaseous exchange in plants

Plants obtain oxygen and carbondioxide mainly through their leaves. They also use lenticels (raised pores found on stems of woody plants) for exchanging minute amounts of gases. They require oxygen for respiration and carbon dioxide for photosynthesis. These gases diffuse into the intercellular spaces of the leaf through stomatal pores which are normally found on the underside of the leaf and the gases diffuse into the cells that require them (Figure 6.8). The lenticel is a porous tissue consisting of cells with large intercellular spaces in the periderm of secondarily thickened organs; the bark of woody stems, and roots of dicotyledonous flowering plants. Like the stomata, it functions as a pore that provides a pathway for the direct exchange of gases between internal tissues and the atmosphere.

Stomatal opening and closing

The opening and closing of stomata depends on changes in the turgor pressure of the guard cells. When water flows into the guard cells by osmosis, their turgor increases and they expand. Due to the relatively inelastic inner wall, the guard cells bend and draw away from each other, allowing the opening of the pore, hence the air passes into the leaf. If the guard cells lose water, the opposite happens and the pore closes. The guard cells lower their water potential to draw in water from the surrounding epidermal cells by actively accumulating potassium ions. This process requires energy in the form of ATP. The energy is supplied by the mitochondria that are found in the guard cells.

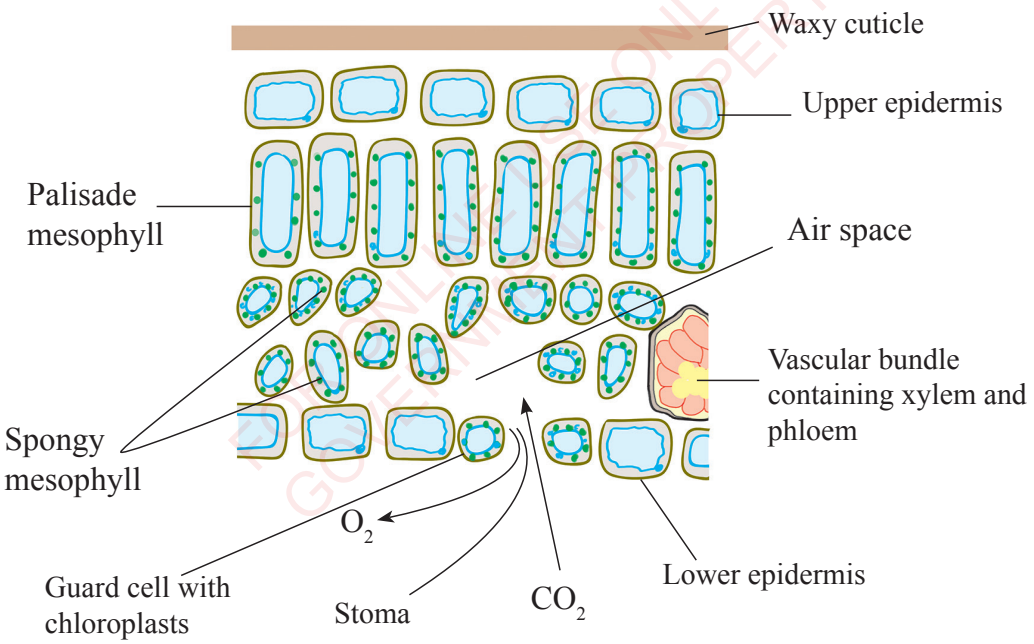


Figure 6.8 Internal structure of a leaf showing the position of stomata for gaseous exchange

The process of respiration in plants occurs throughout the day and night, providing energy to the plants. The light dependent phase of photosynthesis can only occur during the day time and stops at night or during darkness. One product of respiration is carbon dioxide gas. This can be used by the plant directly for photosynthesis. However, during the day, the rate of photosynthesis can be 10 or even 20 times faster than respiration (depending on light intensity). Therefore, the stomata must stay open for longer periods to allow adequate diffusion of carbon dioxide from the atmosphere into the plant cells.

Activity 6.2 Observation of stomata on a plant leaf

Materials

A potted *Tradescantia* plant, water, forceps, needle, surgical or razor blade, watch glasses, light microscope, slide, slide cover, blotting paper, safranin, and glycerin.

Procedure

a) Remove a healthy leaf from the potted plant.
b) Use a surgical or razor blade and forceps to remove a thin outer layer from the lower surface of the leaf. (Alternatively, you can do this by folding the leaf, and gently pulling the thin layer apart using forceps).
c) Place the leaf layer in a watch glass containing water.
d) Add a few drops of safranin stain in a watch glass containing a thin layer of the leaf, then leave it for 2-3 minutes.
e) Using forceps and a needle, take out the layer of the leaf and place it on a slide.
f) Add a drop of glycerin over the leaf layer to prevent the leaf layer from getting dry, then place a slide cover over it.
g) Use a blotting paper to remove the excess stain and glycerin.
h) Observe the leaf layer on a slide under the microscope.

Questions

1. Draw and label what you have observed.
2. What conclusion can you make from your observation?

Safety precaution

Be careful when working with sharp objects such as needle, surgical or razor blade.

Exercise 6.2

1. Explain the factors that govern efficient gaseous exchange at the respiratory surfaces.
2. Describe the adaptations of mountain climbers or dwellers to oxygen uptake.
3. Explain the mechanisms of gaseous exchange in plants.
4. Discuss why it is not advisable to sleep in a room with air-tight windows while the burning charcoal or potted plants are inside.
5. Explain how partial pressures of CO_2 and O_2 may influence the process of gaseous exchange in plants and animals.

6.3 Respiration

Respiration is a process by which food substances are oxidised to release energy in the form of ATP, which is needed for metabolic activities in the body. Respiration takes place within the mitochondria of a cell. Since respiration takes place in a living cell, it is commonly referred to as cellular respiration. There are two types of respiration, namely aerobic respiration and anaerobic respiration. Aerobic respiration occurs in the presence of oxygen, while anaerobic respiration occurs in the absence of oxygen (due to that, it is sometimes referred to as fermentation). Aerobic respiration involves three main stages or processes, namely glycolysis, Kreb's cycle, and oxidative phosphorylation. Respiration is an important process as it yields chemical energy in the form of ATP, which enables organisms to perform life activities such as movement, growth, excretion and reproduction. Respiration process involves oxidation of organic compounds known as respiratory substrates. These are carbohydrates, fats, or proteins.

Respiratory substrates and their energy value

Different respiratory substrates release different amounts of energy (Table 6.2). The difference in energy values of respiratory substrates is due to the amount of hydrogen atoms present in each substrate. The more hydrogen atom in the molecule of a respiratory substrate, the more energy (ATP) is generated during respiration. Mitochondria synthesize water using the hydrogen atoms removed from organic molecules, such as glucose, and the oxygen atoms they take in as they respire. So, the more the hydrogen bonds are broken, the larger the amount of energy released. Lipids' energy density is more than twice that of carbohydrates because of their long fatty acid tails with large number of hydrogen atoms.

Table 6.2 Respiratory substrates and their energy values

S/N	Respiratory substrate	Energy value (KJ/g)
1	Carbohydrates	15.8
2	Lipids	39.4
3	Protein	17.0

a) Carbohydrates

These are the main respiratory substrates used by most respiring cells. Carbohydrates include polysaccharides, disaccharides, and monosaccharides. Polysaccharides such glycogen, cellulose, and starch must be hydrolysed into simple monosaccharides such as glucose; in contrast, disaccharides have to undergo hydrolysis into three monosaccharides, namely glucose, galactose, and fructose, depending on the type of the disaccharide that has been hydrolysed. Monosaccharides are usually in the form of hexose sugars. After their production, they are then utilized in the respiratory pathways to release energy.

b) Lipids (fats and oils)

Lipids can be used as a respiratory substrate when the carbohydrates are exhausted. When hydrolysed, each molecule releases three fatty acids and one glycerol molecule. Fatty acid are energy-rich compounds that enter the respiratory pathways in order to release energy.

c) Protein

Generally, protein is not used as an energy source unless the body has no other option. When all carbohydrate and lipid reserves are fully utilised, proteins come into use. Proteins are not used in the first place because of the variety of vital roles they play in the body. Proteins are hydrolysed into amino acids and then deaminated. Deamination involves the removal of the amino group. The remaining acid may enter the Kreb's cycle directly or may be converted into fatty acids before they enter the Kreb's cycle. The amount of ATP produced from protein metabolism is slightly less than glucose metabolism for equivalent weights.

Respiratory reactions

There are two fundamental types of reactions in cellular respiration, and these are oxidation or decarboxylation.

Oxidation. During respiration, oxidation can take place in three ways; through addition of oxygen, removal of hydrogen (dehydrogenation) removal of electrons.

Decarboxylation. Decarboxylation is the removal of carbon from a compound to form carbon dioxide. For a glucose molecule which contains carbon, hydrogen and oxygen, it is the hydrogen which is required for respiration. Thus, carbon has to be removed by decarboxylation.

Glycolysis

Cellular respiration occurs in all living organisms. Glycolysis is the first stage of cellular respiration whereby glucose is oxidised into pyruvate. This process takes place in the cytoplasm of the cell and it does not require the presence of oxygen. Physiologically, glycolysis produces energy at a high rate, but for a short duration. In anaerobic condition, pyruvate can be reduced to lactate by lactate dehydrogenase. Anaerobic glycolysis is also an effective means of energy production during short intense exercise. Under aerobic condition pyruvate is converted to Acetyl CoA and continues to the citric acid cycle (Kreb's cycle) in the mitochondria. Pyruvate can also be converted to ethanol and CO_2 (fermentation) in anaerobic conditions and allows cells to make small amounts of ATP.

Some cells such as yeast are unable to carry out aerobic respiration and will automatically move into a type of anaerobic respiration called alcoholic fermentation. This occurs with the help of the enzyme pyruvate decarboxylase which removes a carbon dioxide molecule from the pyruvate to yield an acetaldehyde. The acetaldehyde is then reduced by the enzyme alcohol dehydrogenase, which transfers the hydrogen from NADH to the acetaldehyde to yield NAD and ethanol.

Glycolysis process

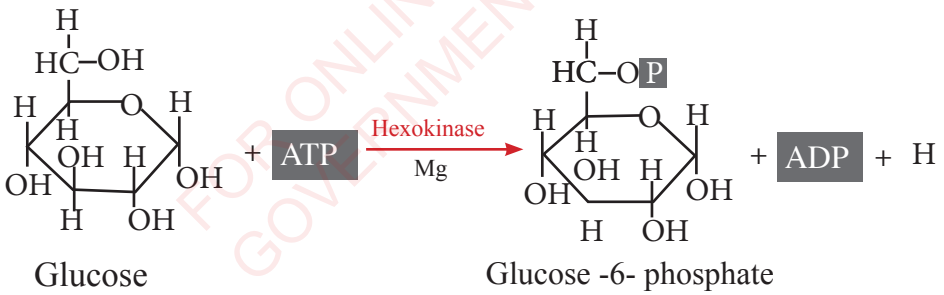
Normally, glycolysis is a determined sequence of ten enzyme-catalyzed reactions and each step is facilitated by a different enzyme. The intermediates provide entry points to glycolysis, although, usually starts with glucose or glycogen to produce glucose-6-phosphate. The starting points for other monosaccharides such as galactose and fructose can be converted into one of these intermediates.

All the reaction steps for the glycolysis take place in the cytoplasm. Glycolysis yields an overall of two molecules of ATP which are free energy-containing molecules, two molecules of pyruvic acid and two "high energy" electron carrying molecules of Nicotinamide Adenine Dinucleotide (NADH). Glucose can also be synthesized from non-carbohydrate precursors by reactions referred to as gluconeogenesis. The pentose phosphate pathway enables cells to convert glucose-6-phosphate, a derivative of glucose, to ribose-5-phosphate and other types of monosaccharides. The NADH is an important cellular reducing agent, which is also produced by this pathway. Generally, glycolysis involves three main stages, namely phosphorylation of glucose, lysis and oxidation by dehydrogenation.

a) Phosphorylation of glucose

Phosphorylation refers to the addition of the phosphate group (Pi) in an organic molecule. In this stage of phosphorylation, two phosphate groups attach to the glucose in order to make it more reactive. In the first step of glycolysis, a phosphate group from ATP is transferred to glucose producing glucose-6-phosphate, a more reactive form of glucose. The enzyme hexokinase, with broad specificity catalyzes the phosphorylation of six-carbon sugars by addition of a phosphate group to glucose in the cell's cytoplasm. The enzyme hexokinase splits ATP into ADP and the Pi is added on to the glucose. Phosphorylation prevents transport of glucose out of the cell and increases the reactivity of the oxygen in the resulting phosphate ester. The negative charge of the phosphate prevents passage of the sugar phosphate through the plasma membrane, trapping glucose inside the cell.

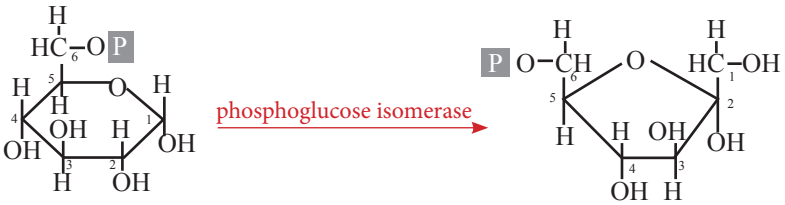
$$\text{Glucose } (C_6H_{12}O_6) + \text{ATP} \xrightarrow[\text{Mg}]{\text{Hexokinase}} \text{Glucose 6-phosphate } (C_6H_{11}O_6P) + \text{ADP} + \text{H}$$



Glucose

Glucose -6- phosphate

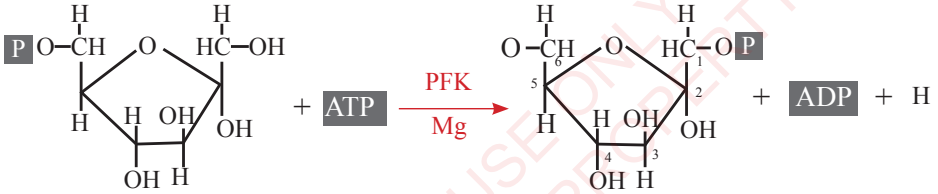
The first product of phosphorylation of glucose is glucose-6-phosphate, which is isomerized to fructose-6-phosphate by phosphoglucose isomerase enzyme.



Glucose -6-phosphate Fructose -6- phosphate

Fructose-6-phosphate is further phosphorylated to fructose-1,6-biphosphate, under the enzyme phosphofructokinase (PFK) and another ATP molecule is used to transfer a phosphate group to fructose-6-phosphate to form fructose 1, 6-biphosphate. The new hydroxyl group on C-1 is phosphorylated by ATP. Another purpose for phosphorylation is to prevent any later product from diffusing out of the cell because charged molecules cannot easily cross membranes. The entry of sugars into glycolysis is controlled at this step, through regulation of the enzyme phosphofructokinase.

Fructose-6-phosphate ($C_6H_{11}O_6P$) + ATP $\xrightarrow{\text{phosphofructokinase}}$ ADP + Fructose-1,6-bisphosphate ($C_6H_{10}O_6P_2$).



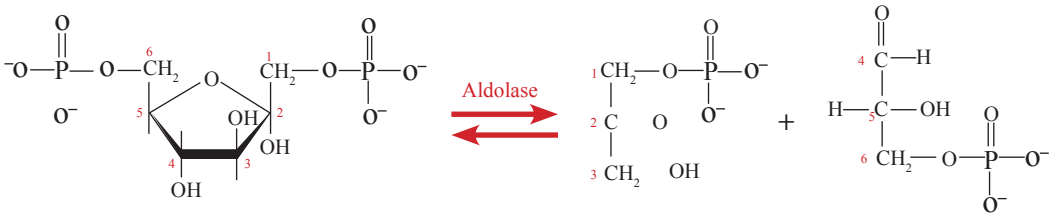
Fructose -6-phosphate Fructose 1-6-bisphosphate

The phosphofructokinase catalysed reaction is irreversible under cellular conditions, and therefore, is the first committed step in glycolysis.

b) Lysis

In this stage the phosphorylated 6-carbon sugar is broken down with the help of enzymes into two 3-carbon sugar phosphate. The enzyme aldolase splits fructose 1, 6-biphosphate into two sugars that are isomers of each other. These two sugars are dihydroxyacetone phosphate and glyceraldehyde phosphate also known as glyceraldehyde-3-phosphate or 3-phosphoglyceraldehyde (3-PGAL). Only the glyceraldehyde 3-phosphate can proceed immediately through glycolysis. Dihydroxyacetone phosphate must be isomerised to glyceraldehyde-3-phosphate by the enzyme phosphotriose isomerase to continue with the next steps of the glycolytic pathway.

Fructose 1, 6-biphosphate ($C_6H_{10}O_6P_2$) + aldolase ↔ Dihydroxyacetone phosphate ($C_3H_5O_3P$) + Glyceraldehyde phosphate ($C_3H_5O_3P$)



Fructose-1-6-bisphosphate | Dihydroxyacetone phosphate | Glyceraldehyde-3-phosphate

c) Oxidation by dehydrogenation

In this step, an enzyme removes one hydrogen atom and two electrons from each three-carbon molecules. Both hydrogen atoms are modified to hydrogen ions, positively charged particles. The hydrogen ion and two electrons from each three-carbon molecule are transferred as a unit to a large molecule called Nicotinamide Adenine Dinucleotide (NAD) to form two molecules of reduced NADH. The hydrogen ions and electrons stored in each molecule of NADH are used to make ATP in later stages of cellular respiration during oxidative phosphorylation of the electron transport chain.

In the final steps of glycolysis, two hydrogen atoms are removed from each three-carbon compound. These hydrogen atoms bond to free-floating oxygen atoms in the cytoplasm to form water. This step prepares the two three-carbon compounds for action by the next enzyme in the pathway. This enzyme removes the phosphate group from each of the three-carbon compounds. Each phosphate group then bonds to a single molecule of adenosine diphosphate (ADP). ADP is composed of three carbon-based rings and a tail of two phosphate groups. The addition of the third phosphate group to the tail forms ATP. In this step, two new ATP molecules are produced; this is the substrate-level phosphorylation. When cells require energy, another enzyme breaks off the third phosphate group, releasing energy that powers the cell. The removal of the third phosphate from ATP converts ATP back to ADP, which is used again in cellular respiration to make more ATP.

When the two 3 carbon compounds are separated from the phosphate groups, the three-carbon compounds are converted to two molecules of pyruvate, each composed of three carbons, three oxygen, and three hydrogen atoms. When glycolysis is complete, important products are produced; two molecules of NADH, two molecules of pyruvate (pyruvic acid) and two molecules of ATP. NADH and pyruvate are used in the next steps of cellular respiration and the ATP molecules are used for reactions in the cell that require energy.

The process can be detailed as follows: Glyceraldehyde -3- phosphate or 3-phospho-glyceraldehyde (3-PGAL) is converted to 1, 3-biphosphoglycerate or 1, 3-diphosphoglyceric acid (1,3-diPGA) by glyceraldehyde-3-phosphate dehydrogenase enzyme where NAD is reduced to $NADH_2$. Then 1,3-diPGA is converted to 3-phophoglycerate or 3-phosphoglyceric acid (3-PGA) by phosphoglycerate kinase enzyme, this process involve the loss of phosphate group (Pi) from 1,3-diPGA to form (3-PGA), and the Pi is transferred to a molecule of ADP to form the first ATP molecules. Actually, two molecules of ATP are formed because there were two triose phosphate produced in the lysis of Fructose-1,6-biphosphate. But the two ATP formed are used to pay back the initial ATP used during the first process of glycolysis (phosphorylation of glucose stage).

The formed 3-PGA is converted to 2-phosphoglycerate or 2-phosphoglyceric acid (2-PGA) by phosphoglyceromutase (phosphoglycerate mutase) enzyme. This enzyme rearranges the phosphate group from the third carbon of 3-PGA to the second carbon, hence forming 2-PGA. The 2-phosphoglycerate is then converted to phosphoenol pyruvate (PEP) under the influence of enolase enzyme, in this reaction water molecule is removed from 2-phosphoglycerate. Then the phosphoenol pyruvate is converted into pyruvate (pyruvic acid) by pyruvate kinase enzyme, where by the phosphate group (Pi) from PEP is transferred to ADP molecule and combine to form ATP molecule. Again two molecules of ATP and two pyruvate are formed; as explained earlier, because the triose phosphate has to enter twice in the glycolysis process that is; when 3-PGAL is used, the dihydroxyacetone phosphate is converted to 3-PGAL and enters the cycle. The formation of pyruvate ends the glycolysis process. (Figure 6.9).

Exercise 6.3

1. Discuss the role of enzymes in a glycolytic pathway.
2. What would happen if the first enzyme in glycolysis is irreversibly inhibited by a toxic substance?
3. Starting with glucose, write the overall reaction for aerobic respiration.
4. What are the main stages of aerobic respiration? List down the important materials that are involved in each stage.
5. The initial stages of glycolysis involve the use of ATP. Explain.

The fate of pyruvic acid

The pyruvate produced during glycolysis has two possible fates, depending on the availability of oxygen in the cell. In the presence of oxygen, the pyruvate will enter Kreb's cycle in which they will be completely oxidised into carbon dioxide and water. Alternatively, in the absence of oxygen (in anaerobic condition) the pyruvate will undergo fermentation.

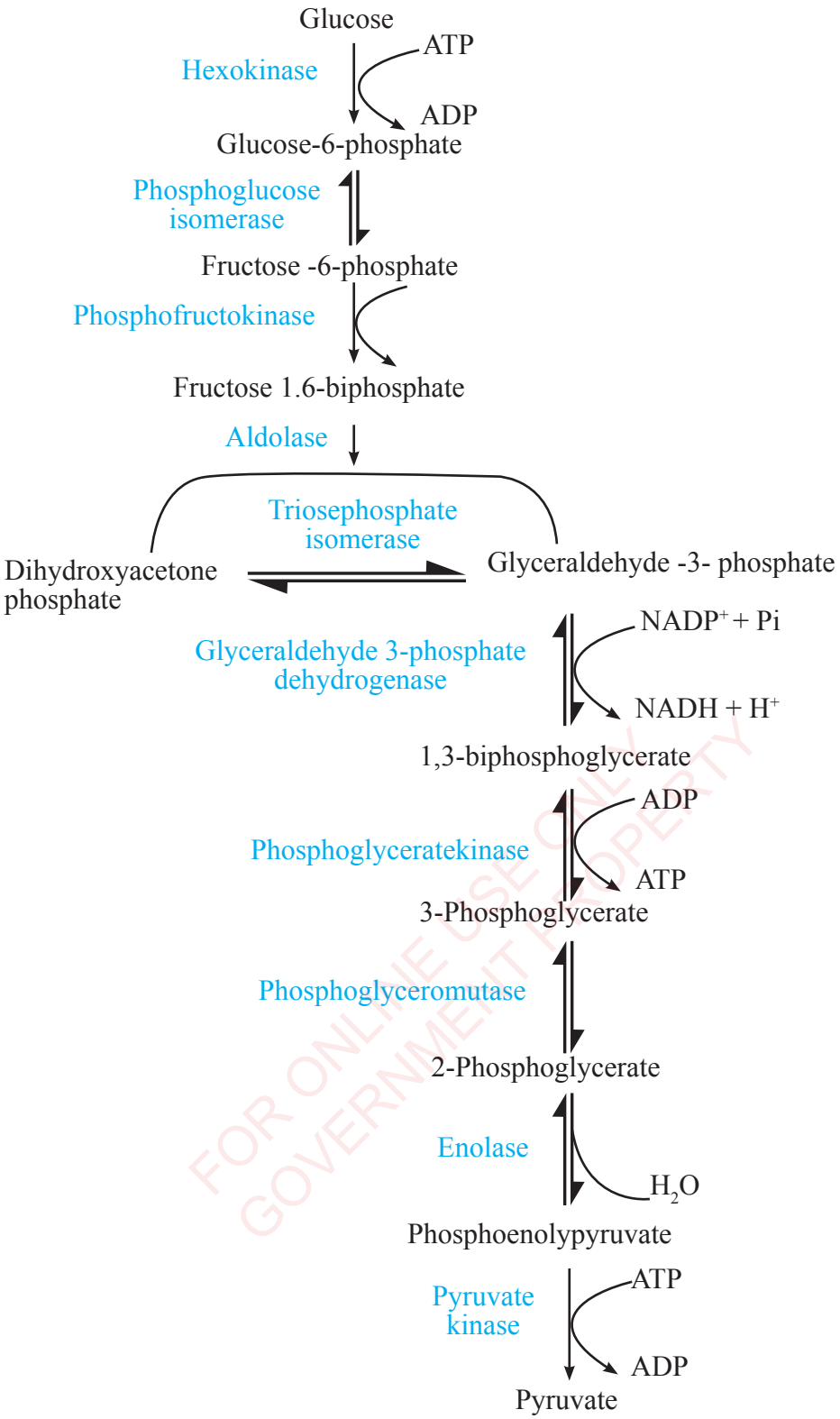


Figure 6.9 The glycolysis process

The fate of pyruvic acid under aerobic respiration

In aerobic respiration, the pyruvate from glycolysis is completely oxidised to carbon dioxide and water using oxygen. In the first stage, pyruvic acid is broken down to carbon dioxide and hydrogen. This occurs in the matrix of mitochondria and involves the Kreb's cycle. In the second stage, hydrogen is oxidised by oxygen to water in a series of reactions that constitute the respiratory chain or electron transport system. This occurs on the cristae of the mitochondria.

The transition between glycolysis and Kreb's cycle

There is a transitional stage between glycolysis and Kreb's cycle or tricarboxylic acid (TCA) cycle. During this stage, each pyruvic acid molecules enters the matrix of the mitochondrion where it undergoes two types of reactions:

a) Decarboxylation, by losing a carbon atom as carbon dioxide: The products of this oxidative decarboxylation (acetyl) are carried by coenzyme A (CoA) resulting into formation of acetyl Coenzyme A (acetyl CoA).
b) Oxidation by dehydrogenation, in the presence of dehydrogenase enzyme and NAD.

The Kreb's cycle

Kreb's cycle is also known as citric acid cycle. When oxygen is available the pyruvate produced during glycolysis enters Kreb's cycle, named after Sir Hans Adolf Krebs (1900-1981), who worked out the details of the cycle in 1930. Kreb's cycle takes place in the matrix of the mitochondrion.

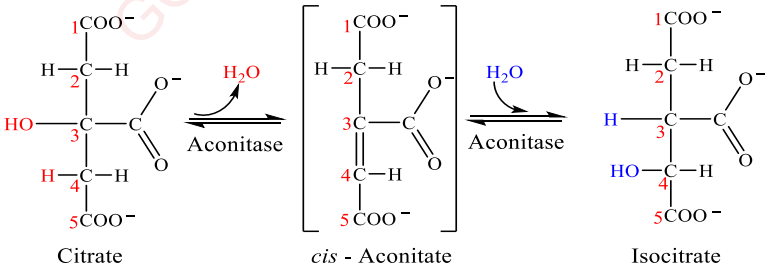
Steps involved in the Kreb's cycle

The Kreb's cycle consists of a series of enzyme-catalysed reactions. It involves the following steps:

The first step is the reaction of acetyl-CoA with oxaloacetate to form citrate, in which the acetyl CoA (2C) is joined to oxaloacetate (4C) to form citrate (6C). This process requires the input of water, and it is catalysed by citrate synthetase enzyme.

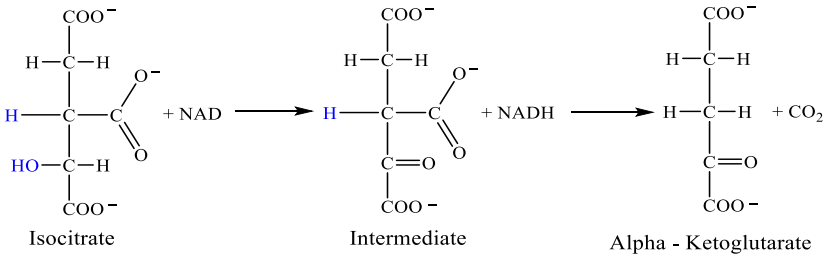
$$\text{Acetyl - CoA + Oxaloacetate + } H_2O \xrightarrow{\text{Citrate synthetase}} \text{Citrate + Coa-SH}$$

The second step is the formation of isocitrate. In the presence of aconitase enzyme, citrate is converted into isocitrate. This process is accomplished by dehydration and rehydration to yield an isomer called isocitrate.

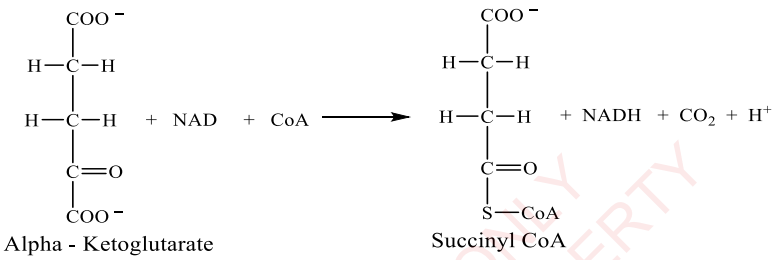


Citrate — *cis* - Aconitate — Isocitrate

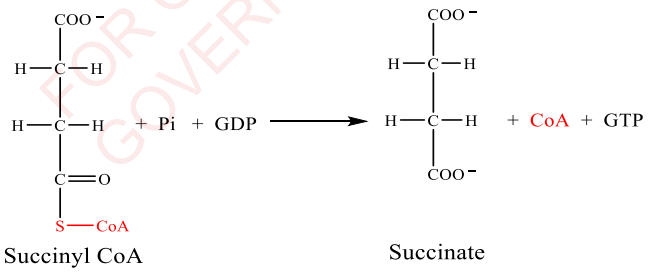
The third step of reaction is oxidation of Isocitrate. In this reaction the Isocitrate is oxidatively decarboxylated to form α- ketoglutarate. The enzymes involved are isocitrate dehydrogenase and oxalosuccinate decarboxylase together with NAD, and the products are $NADH_2$ and CO_2.



The fourth step is the oxidation of α- Ketoglutarate to form Succinyl – CoA. In the presence of α- ketoglutarate dehydrogenase enzyme, α- ketoglutarate is oxidatively decarboxylated to form succinyl CoA (4C). During this reaction NAD^+ is reduced to $NADH_2$. The products are $NADH_2$ and CO_2.



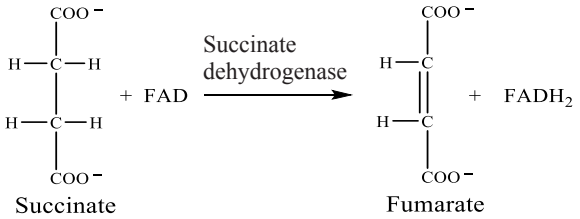
The fifth step is the conversion of Succinyl CoA into succinate. This reaction is catalysed by an enzyme succinyl CoA synthetase. It involves the removal or loss of CoA from succinyl – CoA. The CoA is replaced by phosphate group which is then removed and attached to guanosine diphosphate (GDP), thereby forming guanosine triphosphate (GTP). GTP is an energy yielding molecule and is used to generate ATP when it donates a phosphate group to ADP.



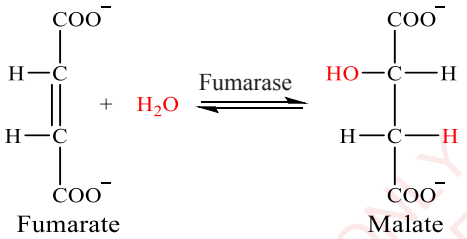
There are two forms of the enzyme, called isoenzymes, for this step, depending upon the type of animal tissue in which they are found. One form is found in tissues that use large amounts of ATP, such as heart and skeletal muscle. The second form of

the enzyme is found in tissues that have a high number of anabolic pathways, such as liver. This form produces guanosine triphosphate (GTP). GTP is energetically equivalent to ATP; however, its use is more restricted. In particular, protein synthesis primarily uses GTP.

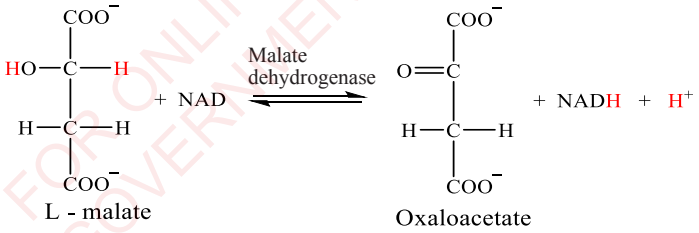
The sixth step is the oxidation of succinate to form fumarate. The conversion of succinate into fumarate involves removal of hydrogen and is catalysed by succinate dehydrogenase. In this reaction FAD is reduced to $FADH_2$.



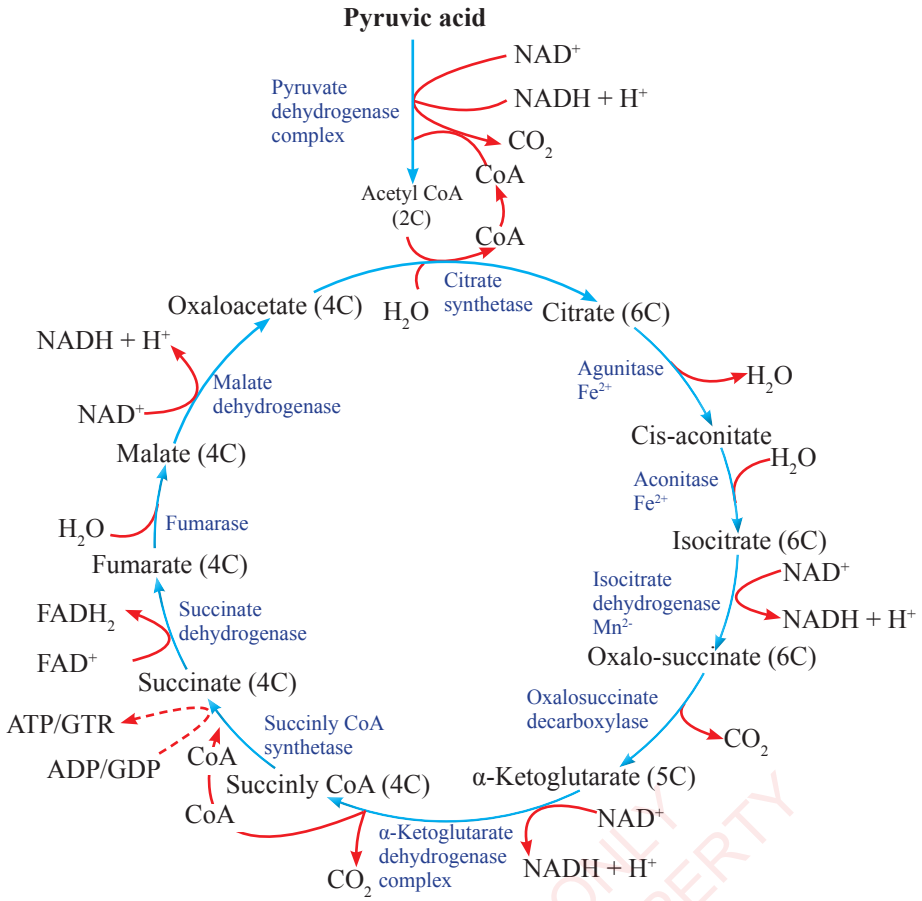
The seventh step is the hydration of fumarate to malate. This reversible reaction is catalysed by fumarase, which is also known as fumarate hydratase.



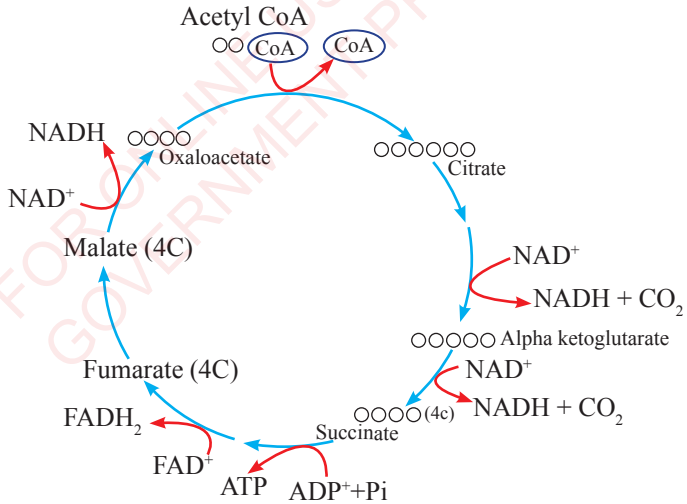
Eighth step is the oxidation of malate to form oxaloacetate. This reaction is catalysed by malate dehydrogenase and results in the production of oxaloacetate which is the starting compound of the Kreb's cycle. In this process, NAD is reduced into $NADH_2$.



It is important to note that glycolysis yields two pyruvate molecules, each of which enters the Kreb's cycle separately. Thus, for a molecule of glucose, there must be two Kreb's cycles, and, to avoid repetition, each component of the cycle must be multiplied by two. Thus, the products of the Kreb's cycle are $6NADH_2$, $2FADH_2$, $4CO_2$, 2ATP, and oxaloacetate molecules. The transitory step, that is from pyruvate to acetate, yields $2NADH_2$ and $2CO_2$ molecules (Figure 6.10 (a) and (b)).



(a)



(b)

Figure 6.10 Kreb's cycle (a) detailed diagram and (b) simplified diagram

Importance of the Kreb's cycle

Kreb's cycle is an economical way of turning food components in the cell into usable energy. Only the acetyl groups are destroyed in the cycle. The seven enzymes that carry out the various reactions and the intermediate compounds on which these enzymes act can be used again and again.

Moreover, many of the intermediate compounds produced in the Kreb's cycle are of value as starting materials for the synthesis of amino acids, carbohydrates, and other cellular products. Pyruvates are broken down to carbon dioxide. Thus, the Kreb's cycle degrades macromolecules into simpler molecules. The Kreb's cycle releases ATP and NADH and FADH. The ATP is directly utilised by the cellular activities while the NADH and FADH are metabolites for oxidative phosphorylation of the electron transport system in which ATP are produced.

The fate of pyruvic acid under anaerobic condition

In the absence of oxygen; the principle product of glycolysis (pyruvate) enters a fermentation process. The organisms that do not use oxygen as the final proton and electron acceptor are known as anaerobes. In anaerobes, other less-oxidising substances such as sulphate ion (SO_4^{2-}), nitrate ion (NO_3^-), sulphur, and fumarate are used. These terminal electron acceptors have smaller reduction potentials than oxygen. This means that less energy is released per oxidised molecule. Generally, anaerobic respiration is less efficient in energy production than aerobic respiration. It is mainly used by prokaryotes that live in environment devoid of oxygen. Many anaerobic organisms are obligate anaerobes as they can only respire anaerobically and they die in the presence of oxygen. Muscles do also respire anaerobically whenever there is deficiency or lack of oxygen at a particular tissue point. This creates the basis for categorising anaerobic respiration into alcoholic fermentation and lactic acid fermentation.

Alcoholic fermentation

Alcoholic fermentation is also called ethanol fermentation which occurs in cells, such as plant and yeast cells (Figure 6.11). This biological process converts two pyruvates into two acetaldehydes producing two carbondioxide molecules as a waste product. The two acetaldehydes are then converted to two ethanol molecules by using hydrogen ions from NADH; converting NADH back into NAD^+. Ethanol fermentation has many uses. These include producing alcoholic beverages, ethanol fuel, as well as raising reagent in baking bread.

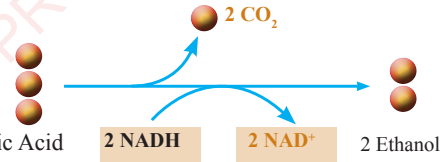


Figure 6.11 Alcoholic fermentation pathway

Lactic acid fermentation

This is also referred to as lactate fermentation, which is a biological process by which pyruvate is converted into the metabolite lactate. In lactic acid fermentation, the pyruvic acid from glycolysis is reduced to lactic acid by NADH, which is oxidised to NAD^+. Lactic acid fermentation allows glycolysis to continue by ensuring that NADH is

returned to its oxidised state (NAD^+). This anaerobic fermentation reaction occurs in some bacteria and animal cells such as in muscle cells (Figure 6.12).

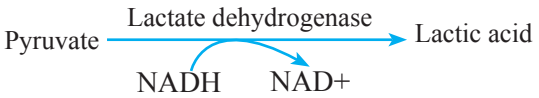


Figure 6.12 Lactic acid fermentation pathway

If oxygen is present in the cell, many organisms will bypass fermentation and undergo aerobic respiration. However, facultative anaerobes will undergo both fermentation and aerobic respiration in the presence of oxygen. Sometimes, even when oxygen is present and aerobic metabolism is taking place in the mitochondria, if pyruvate is building up faster than it can be metabolised, the fermentation process will occur. The enzyme responsible for catalysing the interconversion of pyruvate to lactate is known as lactate dehydrogenase.

Exercise 6.4

1. What is the Kreb's cycle pathway? How is it related to glycolysis?
2. Illustrate the steps involved in the Kreb's cycle.
3. What is the importance of regeneration of oxaloacetate in the final step of Kreb's cycle?
4. Carry out library search to find out if the bacteria and yeast form alcohols in the absence of oxygen or they possess a metabolic pathway that does not involve oxygen. Write down your findings.
5. Explain the fate of pyruvic acid during respiration.

Events of electron transport chain in the formation of ATP

The electron transport chain is the final and most important step of cellular respiration. The electron transport chain (electron transport system or cytochrome system) is a process by which the energy carrier molecules ($NADH_2$ and $FADH_2$) produced during glycolysis, Kreb's cycle and other catabolic processes are oxidized to release energy in the form of ATP. The electron transport chain is a series of electron transporters embedded in the inner mitochondrial membrane that shuttles electrons from $NADH_2$ and $FADH_2$. In the process, protons are pumped from the mitochondrial matrix to the intermembrane space, and oxygen is reduced to form water.

The hydrogen atoms carried by reduced NAD and FAD are transferred to a chain of other carriers at progressively lower energy levels. As the hydrogen passes from one carrier to the next, the energy released is used to combine ADP and inorganic phosphate (Pi) to form ATP. A series of carriers is termed the respiratory chain. The latter has four electron carriers, namely NAD, FAD, coenzyme Q and cytochromes. The hydrogen atoms carried by NAD are shunted into the chain at carrier one, NAD (a step ahead FAD), and produce a total of 3 ATP molecules as they pass through the carriers (Figure 6.13). Meanwhile, the hydrogen atoms carried by FAD are introduced in the chain at carrier two, FAD. Therefore, a pair of hydrogen atoms carried by FAD makes a total of 2 ATP molecules as it passes through the carriers. Initially, hydrogen atoms pass along the chain. However, after the FAD stage, they split into protons (H^+) and electrons. The former takes another route out of the chain as the electrons pass through the cytochrome system.

Accordingly, the pathway can be called the electron transport system. Oxygen is the final electron acceptor in the electron transport system. Finally, protons and electrons recombine to form hydrogen atoms which create a link with oxygen to form water, this reaction is catalysed by the enzyme cytochrome oxidase. The formation of ATP through the oxidation of hydrogen atoms is called oxidative phosphorylation (Figure 6.13).

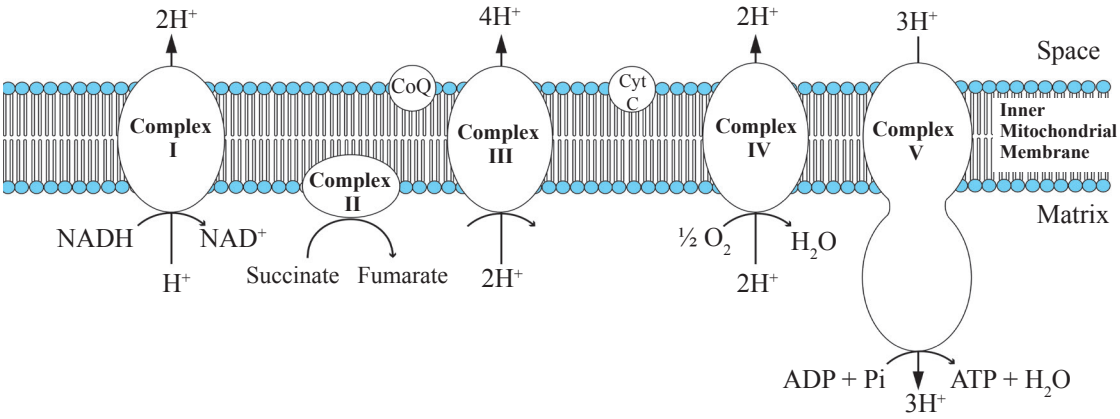


Figure 6.13 Electron transport chain

Generally, in the electron transport chain each reduced NAD molecule results in production of 3 ATP and the release of hydrogen which combines with oxygen to form water. Therefore, the 10 reduced NAD molecules (2 from glycolysis, 2 from conversion of pyruvate to Acetyl CoA and 6 from Kreb's cycle) results in the production of 30 ATP, 10 water molecules and uses 10 oxygen atoms (5 molecules of oxygen). Moreover, each reduced FAD molecule (from Kreb's cycle) results in the production of 2 ATP, hence 2 FAD molecules produce 4 ATP. Overall, the electron transport chain produces a total of 34 ATP molecules from one molecule of glucose (Figure 6.14).

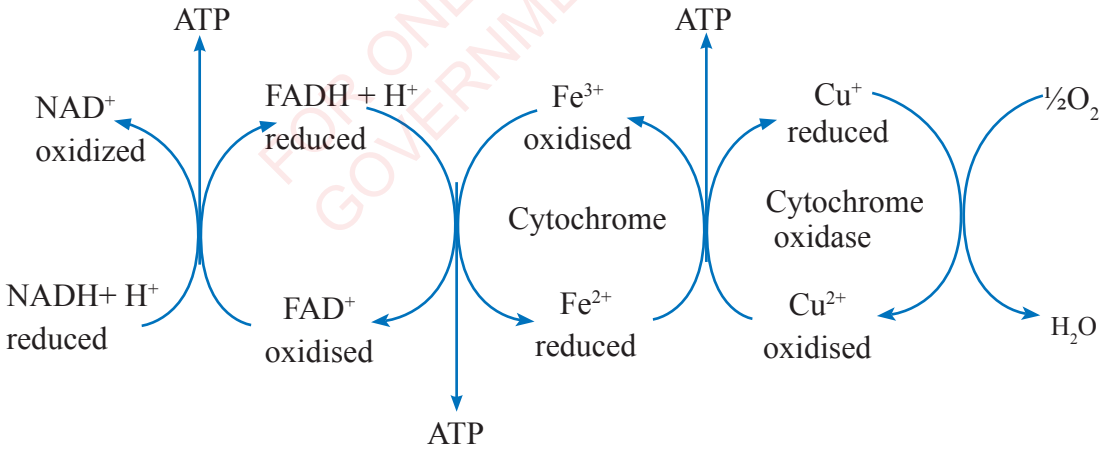


Figure 6.14 ATP produced by NADH and FADH

ATP yield in aerobic and anaerobic respiration of glucose

a) In aerobic respiration

A total of 38 ATP molecules are produced for every one molecule of glucose oxidized completely (Table 6.3). The balanced equation for aerobic respiration is:

$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 38ATP$

$\Delta G = -2880$ kJ per mol of $C_6H_{12}O_6$

Thus, the energy released by complete oxidation of one molecule of glucose is 2880 kJ, the negative ΔG shows that the reaction can occur spontaneously.

The amount of energy contained in one mole of ATP is 30.6 kJ. The amount of energy contained in 38 moles of ATP is 38 x 30.6 = 1162.8 kJ. The efficiency of energy transfer in aerobic respiration is 1162.8/2880 x 100% = 40.4 %.

Table 6.3 Amount of ATP produced from glucose respired aerobically

Respiratory process	Number of NADH (x3ATPs)	Number of FADH (x2ATPs)	ATP direct formed	Total number of ATP Molecules
Glycolysis: glucose to pyruvate	2	-	2	8
Link reaction: pyruvate to Acetyl CoA	2	-	-	6
The Kreb's (TCA) Cycle	6	2	2	24
Total count	10	2	4	38

b) In anaerobic respiration

During alcoholic fermentation 2 molecules of ATP are produced for every molecule of glucose used (Table 6.4). Conversion of glucose to ethanol produces 210 kJ per mole, thus the energy contained in the 2 molecules of ATP is 2 x 30.6 = 61.2 kJ. The efficiency of energy transfer during alcoholic fermentation is 61.2/210 x 100% = 29.1%

Alternatively, in the lactate fermentation, 2 ATP molecules are produced for every molecule of glucose used.

Glucose $\longrightarrow$ 2Lactate + 2ATP

The amount of energy contained in 2 ATP molecules is 2 x 30.6 = 61.2 kJ.

The total energy released during the conversion of glucose to lactate is 150 kJ per mole. Thus, the efficiency of energy transfer during lactate fermentation is 61.2/150 x 100% = 40.8%.

The total energy released when glucose molecule is respired aerobically is 38 ATP, but the total energy released in anaerobic respiration of glucose is only 2ATP. Therefore, aerobic respiration is more efficient than anaerobic respiration.

Table 6.4 Amount of ATP produced from glucose respired anaerobically

Respiratory process	Number of NADH	Number of FADH	ATP direct formed	Total number of ATP molecules
Glycolysis: glucose to pyruvate	2	-	2	2

Respiratory pathway using lipids and protein

Lipids and proteins are respiratory substrates in addition to carbohydrates, which are used by most cells. The respiratory pathways for both aerobic and anaerobic process involve the stages of respiration such as glycolysis, the Kreb's cycle, and electron transport chain. Aerobes use them all, whereas anaerobes use only glycolysis. Lipids and proteins are not directly accommodated in these pathways, they are converted in a form to suit the types of the metabolites required by such pathways (Figure 6.15).

Lipids are polymers of fatty acids and glycerol. They have to be hydrolysed into glycerol and fatty acids. Glycerol can be converted into glucose and follow the patterns in glycolysis to the electron transport chain. The fatty acids join the Kreb's cycle as fatty acid fragments, each with 2 carbons that are joined with Acetyl CoA. The fatty acid will make several Kreb's cycles depending on the number of fragments formed. The products of Kreb's cycles will add up in generating a huge account of ATP from lipids.

Proteins are polymers of amino acids. Amino acids have amino and carboxylic groups. They also have a varied number of carbon atoms. Being polymers, proteins should be hydrolysed into amino acids which are deaminated to remove the amino groups. The remaining portions enter the respiratory pathway depending on the number of carbons each has. The portions with 3 carbons are converted into pyruvate; those with 4 carbons form oxaloacetate while those with 5 carbons are converted into α-ketoglutarate. Example aspartate and glutamate enter directly into the Kreb's cycle at oxalaoacetate and α-ketoglutarate respectively.

Respiratory quotient (RQ)

Respiratory quotient (RQ) is a measure of the ratio of carbon dioxide evolved by an organism to that of oxygen consumed over a given period of time.

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

For example, the equation for a complete aerobic oxidation of hexose sugar is represented below:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

$$RQ = \frac{6CO_2}{6O_2} = 1$$

However, it is difficult to have this theoretically calculated value, because a substrate is rarely completely oxidised.

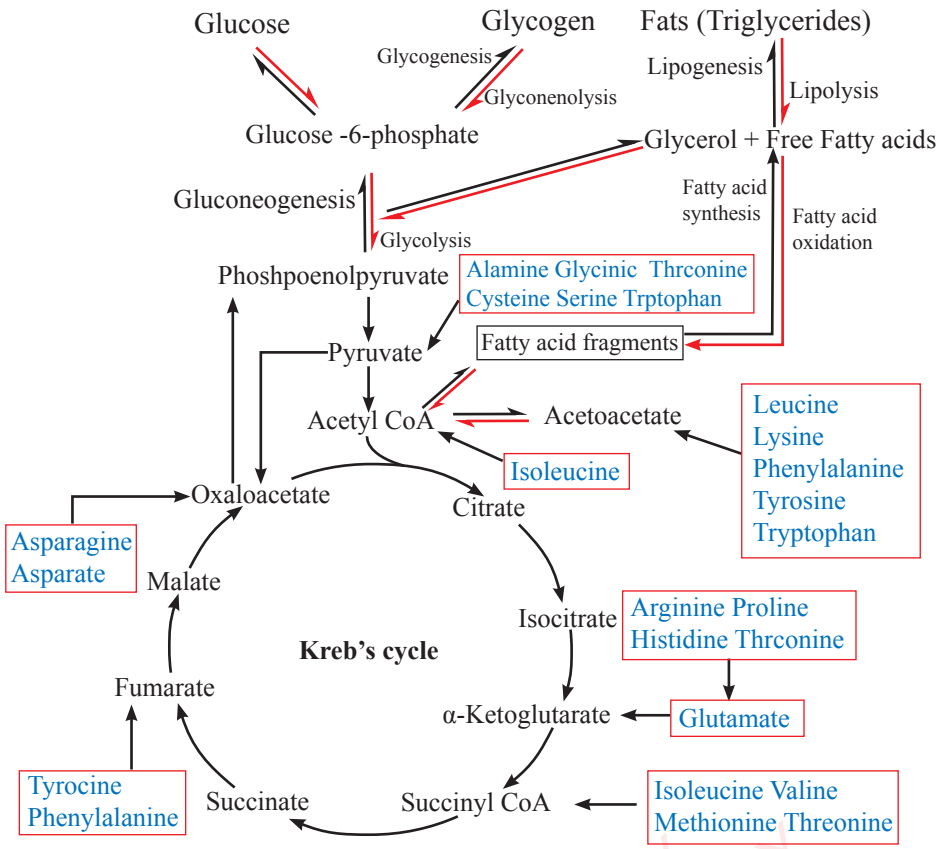


Figure 6.15 Glucose, lipids and proteins metabolism

Significance of RQ

a) It helps to indicate the type of substrate oxidised; for example, the RQ value of 1.0 implies complete oxidation of glucose; RQ of 0.7 means oxidation of fats (fatty acids); and, for proteins, the RQ value varies, but it is around 0.9. The RQ values of less than one means that oxidation of a mixture of substrates.

b) It helps to indicate the type of metabolism taking place. For example, if RQ values are less than one, the following are possible;

   i) Aerobic oxidation, as the volume of carbon dioxide evolved is less than that of oxygen taken in.

   ii) The carbondioxide produced is used by another process in the same organism, for instance photosynthesis in plants or formation of calcareous shells in some animals.

On the other hand, high RQ values imply kinds of anaerobic respiration. Therefore, the volume of carbondioxide evolved is greater than that of oxygen consumed (Table 6.5).

Examples

a) The equation for respiration of the fat tripalmitin is as follows:

$$2C_{51}H_{98}O_6 + 145O_2 \longrightarrow 102CO_2 + 98H_2O$$

What is the RQ for tripalmitin?

Solution:

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

$$RQ = \frac{102O_2}{145O_2} = 0.7$$

So, the RQ value for tripalmitin is 0.7

b) What is the RQ when glucose is respired anaerobically to ethanol and carbondioxide?

Solution:

$$RQ = \frac{\text{Volume of } CO_2 \text{ evolved}}{\text{Volume of } O_2 \text{ consumed}}$$

Since the process is anaerobic, the volume of oxygen evolved is zero.

Thus:

$$RQ = \frac{2CO_2}{0O_2} = \infty \text{ (Infinity)}$$

Table 6.5 RQ values for carbohydrates, lipids and proteins

Respiratory substrate	Respiratory quotient	Type of metabolism
Carbohydrates	1	Aerobic respiration
Lipids	0.7 - 0.72	Aerobic respiration
Proteins	0.8 - 0.9	Aerobic respiration
Carbohydrates or lipids or proteins	∞	Anaerobic respiration

The basal metabolic rate (BMR)

The basal metabolic rate of an organism is the minimum rate of energy conversion required just to stay alive during rest or sleep. It is actually the amount of energy needed to maintain body functioning while at rest, to keep the heart beating, blood flowing, food digested and body breathe. It also referred to as resting metabolic rate (RMR). In humans, BMR is measured after an individual has undergone a standardised rest period of between 12 to 18 hours of physical and mental relaxation without taking a meal during that period.

Factors which cause variation of the BMR of an individual

The following factors influence the variation of basal metabolic rates among individuals:

Body size

Small organisms have larger surface area to volume ratio, hence larger BMR than large organisms.

Body composition

Fat tissue has a lower metabolic activity than muscle tissue. As lean muscle mass increases, the metabolic rate increases.

Sex

The basal metabolic rate (BMR) of females is lower than that of males. In average the BMR of females is 5 to 10 percent lower than that of males. The difference is that; generally, women possess more body fat and less muscle mass than men of similar size.

Age

The BMR decreases with age (aging). A decrease in lean muscle mass during adulthood results in a slow, steady decline in BMR.

Climate and body temperature

The BMR of people in tropical climates is generally up to 20 percent higher than their counterparts in more temperate climates because it takes energy to keep the body cool. Exercise performed in hot weather also imposes an additional metabolic load. Body fat content and effectiveness of clothing determine the magnitude of energy metabolism in cold environments; it takes energy to keep the body warm if you work or exercise in very cold weather.

Hormonal levels

Thyroxine (T4) is the key hormone released by the thyroid glands which has a significant effect upon metabolic rate. Hypothyroidism is relatively common, especially in women near or after menopause. Everyone with a weight problem should have their thyroid function checked by their doctor and treated appropriately if it turns out to be low.

Healthy status

Fever, illness, or injury may increase resting metabolic rate. Therefore, a sick person has higher rate of metabolism than a healthy person.

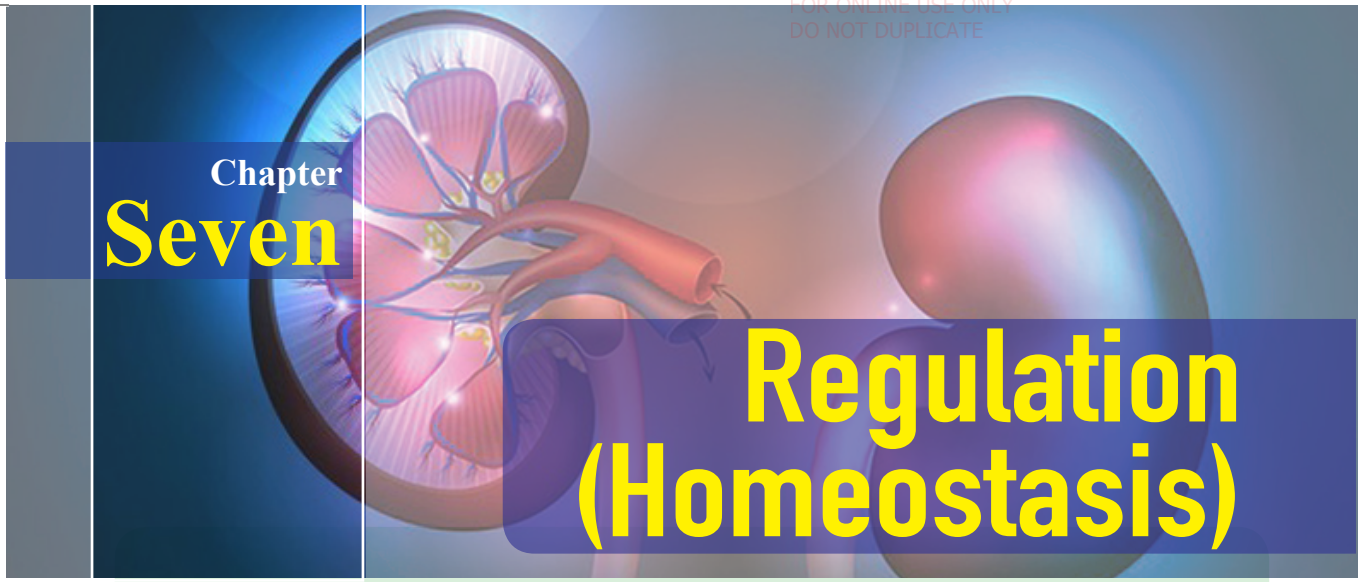
Exercise 6.5

1. Write short notes on Respiratory Quotient (RQ).
2. What is Basal Metabolic Rate (BMR)?
3. Explain the factors that affect the BMR of an organism.

Revision questions

1. How are the lungs adapted to their functions?
2. What is the role of the mucus secreted by the epithelium lining of the nasal passage?
3. Describe the internal structure of the mammalian lungs.
4. Explain the mechanism of carbon dioxide transport in the mammalian blood.
5. Describe the respiratory substrates and their energy value.
6. Describe the stages involved in glycolysis.
7. Describe the fate of pyruvic acid under aerobic and anaerobic respiration.
8. Explain the events in the electron transport chain during the formation of ATP.
9. Explain why NADH gives more ATP than FADH in the electron transport chain.

10. Outline the respiratory pathways when using lipids and proteins as substrates.
11. Why does aerobic respiration produce more energy than anaerobic respiration?
12. Explain the factors that affect the rate of respiration in humans.
13. What is the role of oxygen in respiration?
14. Explain why athletes normally face the problem of muscle fatigue.
15. Making bread, beer, wine and cheese are the processes which involve fermentation. Choose one of these products and describe the involvement of fermentation in the process.



Chapter
Seven

Regulation (Homeostasis)

Introduction

The internal environment of multi-cellular organisms is made up of tissue fluids whose conditions, such as pH, temperature, pressure, glucose concentration and salt contents are always kept at a relatively constant level regardless of the fluctuations of the external environments. The ability to maintain a constant internal body environment enables an organism to survive in a variety of habitats. Keeping a stable internal environment of an organism requires constant adjustments as conditions change inside and outside the cells. Since the internal and external environments of a cell are constantly changing, adjustments must be made continuously to stay at or near the normal level. This regulatory mechanism is called homeostasis. In this chapter, you will learn about the concept of body regulation, temperature regulation, excretion and osmoregulation. You will also learn about the processes through which water content in the body is controlled.

7.1 The concept of regulation

The importance of regulation (homeostasis) in animals was first pointed out by the French physiologist Claude Bernard in 1857. In one of his researches, he used dogs to study the importance of constant internal environment in mammals. He described variations in glucose concentration in the blood. His study revealed that the concentration of glucose in the blood of mammals remained relatively constant regardless of variations in diet. For example, dogs that were well fed with food rich in meat or sugar had similar glucose concentration in the blood as starving dogs. From these results, he concluded that mammals must have a control mechanism that keeps their internal environment constant, despite the changes in external environment. This tendency enables them to exploit a wide variety of habitats. For example, in human beings, the internal mechanism maintains constant body temperature of about 37 ^{0}C despite the wide range of variation in the environmental temperatures. This constancy enables human beings to be active in different environments, while other animals such as amphibians and reptiles have non-constant body temperature and they cannot be active in a wide range of environmental temperatures.

Homeostatic control mechanism

The homeostatic control mechanism involves a regulator which compares the actual output with a set point. Then, it produces some sort of error signal, which sends information to the corrective mechanism or effector regarding the difference between the set point and the actual output. The error signal is usually in the form of nerve impulses or hormones in the body. The corrective mechanism may include one or more effectors that set the controlled system and restore the output to its set point. In some physiological processes, such as temperature regulation, separate but coordinated mechanisms control deviations in different directions from the set point such as the rise or fall in body temperature, and lead to a greater degree of control.

The corrective mechanism explained above is said to be the key component of homeostatic control mechanism. It varies the output so that it can be brought back to the set point. Homeostasis is a dynamic process which works by making continual adjustments to compensate for fluctuations of output. Thus, it is more accurate to describe the homeostatic system as being in a steady state or in a dynamic equilibrium rather than being constant. In addition, homeostatic controls can be either extrinsic or intrinsic. Extrinsic control is one which originates from outside of the body organ or tissue while the intrinsic control is the one which originates from within the body, organ or tissue.

Components of homeostatic mechanism

The homeostatic control mechanism consists of different components, including, a set point, stimulus, variables, receptors, effectors, inputs, outputs, control centre and compensatory response. These components are integrated to bring about homeostatic control (Figure 7.1). A set point is the desired or optimal physiological state for the output. It is also known as the norm or reference point. This is usually determined genetically in the physiological process. In the homeostatic control mechanism variables are factors that are being regulated. Such factors include body temperature, pH, blood pressure, and plasma potassium concentration. Anything that produces change on a variable is called a stimulus. Therefore, a stimulus can trigger changes in various body parameters such as temperature, pH, blood pressure, and plasma potassium concentration, resulting into deviation from a set point. The detectors or receptors tend to detect a change in variables.

Different types of sensory receptors exist, including thermoreceptors which detect change in body temperature. Input communicates the information from the receptor to the control centre. An example of inputs in the homeostatic control mechanism is afferent nervous system. Effectors in the homeostatic control mechanism are organs or glands that carry out the response from the control centre. Examples of effectors include: the sweat glands, blood vessels, and muscles. The control centre of the homeostatic control is the brain, particularly the hypothalamus. The control centre analyses the information from the receptor and determines the appropriate response to the change or stimulus.

The output sends the response instructions from the control centre to the effector.

For example, if the temperature needs to be lowered, the hypothalamus will send the information to the effector for the response. Compensatory response is the action of the effector which will counteract the stimulus and bring the variable back to its normal range.

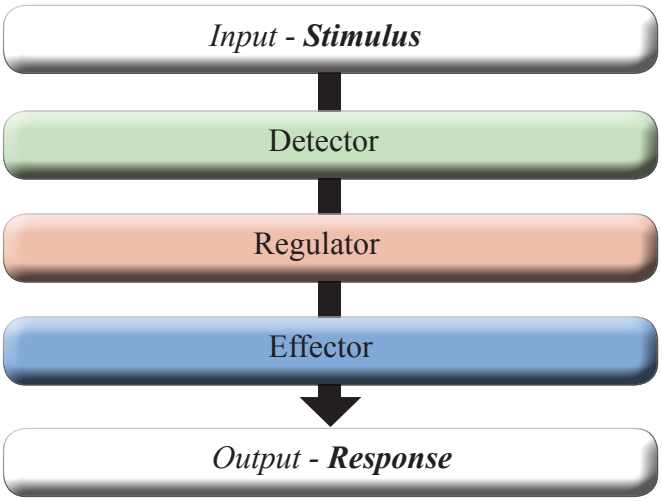


Figure 7.1 Components of the homeostatic control mechanism

Feedback mechanism for homeostatic control

Any change from the set point activates the control system to initiate a sequence of events so as to either restore conditions towards their normal state, or to make the system deviate further. Feedback requires the action of the system to be related to a reference point or set-point (optimum level) of the variable being controlled. Two forms of feedback, namely negative and positive feedback are recognised.

Negative feedback

A negative feedback occurs in a situation where the disturbance in a system sets in motion a sequence of events which tends to restore the system to its original state. A negative feedback in homeostatic control mechanism keeps a variable, such as the blood glucose level close to a particular value or set point (Figure 7.2).

A change in the state of an internal factor in the body causes effectors to restore the internal environment to its original state. For instance, an increase in the level of glucose in the body triggers a sequence of events that tend to remove excess glucose from the blood by converting it into glycogen. In contrast, a decrease in the level of glucose in the body causes the liver to break the stored glycogen to glucose in order to supply more glucose to the cells of the body. This corrective measure allows blood glucose level to remain constant. This type of system in which change in the level of an internal factor causes a corrective mechanism is referred to as a self-adjusting system. The science of a self-regulating control system which operates via feedback mechanisms in organisms is known as cybernetics.

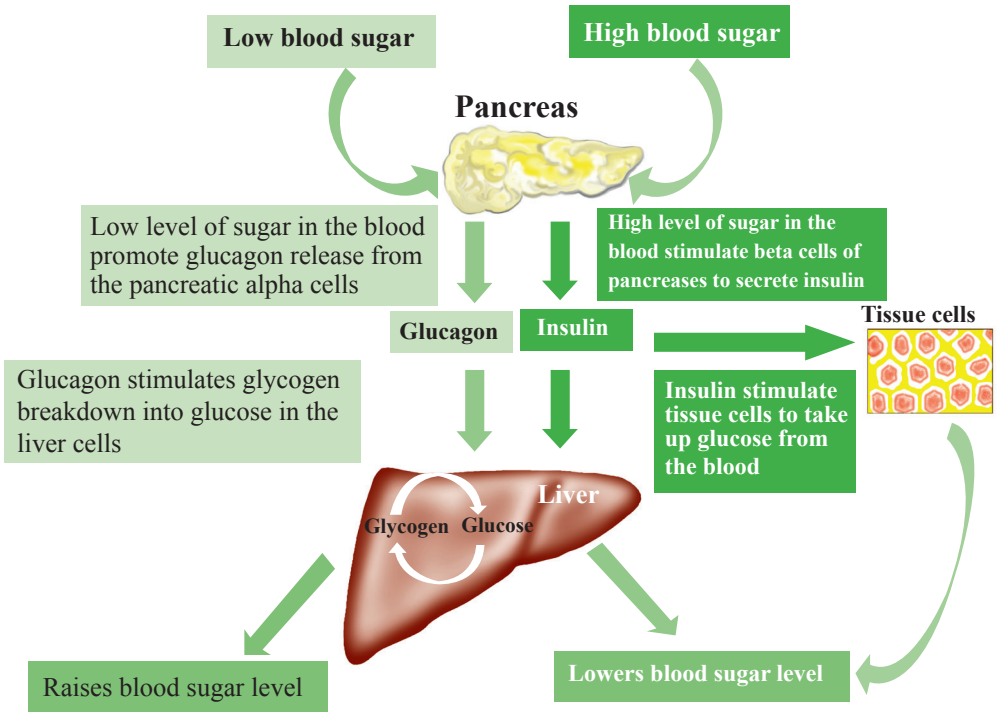


Figure 7.2 Glucose and insulin negative feedback loop

Positive feedback

Positive feedback is the self-regulatory mechanism which operates when the system is deviated from a set point which initiates a sequence of events that tends to deviate further the system. The positive feedback mechanism makes the system to be unstable; that is why it is not common in living organisms. An example of positive feedback occurs during labour, when the hormone oxytocin stimulates muscular contraction of the uterus; which in turn stimulates the release of more oxytocin. Positive feedback mechanism may also occur in the nerves where a small stimulus can bring about a large response to the effectors (Figure 7.3).

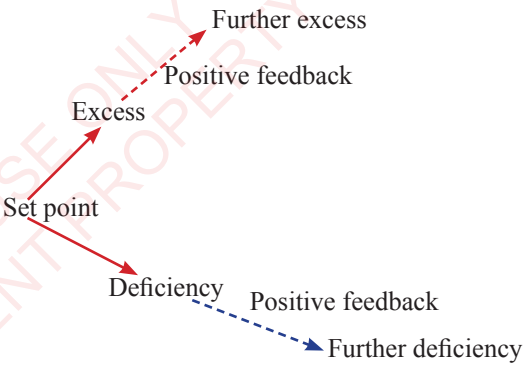


Figure 7.3 A positive feedback mechanism

Another example of positive feedback mechanism is the release of volatile plant hormone (ethylene) by the ripening fruits that accelerates the ripening of unripe fruits in its vicinity. The fruit ripening process involves changing the fruit texture, softening, and colour. As more fruits get ripe they produce more hormones that further continue to ripen more the surrounding fruits.

Activity 7.1 Investigating the effect of positive feedback mechanism in ripening fruit

Materials

One bunch of ten unripe green bananas, six containers, and dry banana leaves.

Procedure

a) Label the six containers from A to F.

b) Isolate five bananas from the bunch and put one banana in each of the five containers labelled B to F.

c) Put the remaining five undetached bananas in the container labelled A.

d) Cover all the containers with dry banana leaves and arrange them in series; starting with the one with five bananas. The distance from one container to another should be not less than one meter (Figure 7.4).

e) Note the number of days it will take for all bananas in all containers to get ripe.

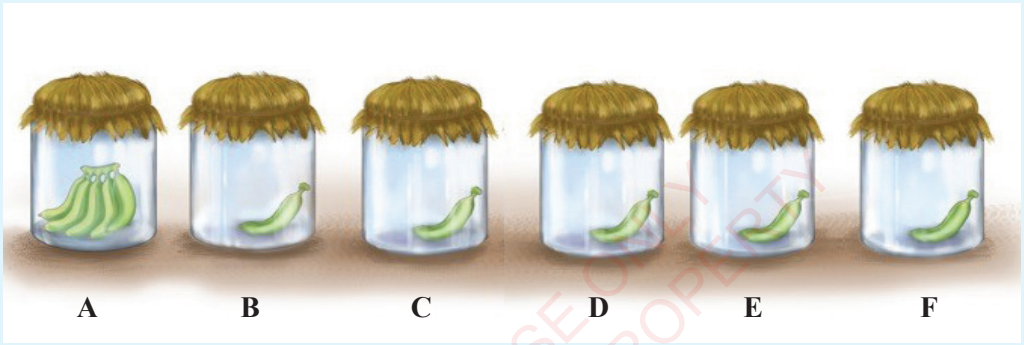


Figure 7.4 Experimental set up for ripening of fruits

Questions

1. Compare the time taken for the bunch and individual bananas to ripen.
2. What might be the cause of the differences in ripening time?
3. Explain the significance of the phenomenon in our everyday life.

Exercise 7.1

1. Briefly explain the concept of regulation (Homeostasis).
2. Describe the components of the homeostatic control mechanism.
3. Explain the feedback mechanisms for homeostatic control.
4. Give a physiological example of a negative feedback control system and clearly describe how it works.

7.2 Temperature regulation

Most organisms can survive in a narrow range of temperature from 10 °C to 30 °C. In order to survive, most animals have to regulate their body temperature. The tendency of animals to adjust their body temperature to suit the living conditions of varying temperatures in the environment is termed as temperature regulation (thermoregulation). Animals with a varying body temperature according to the changes in the environmental temperature are called poikilotherms (*poikilos* means 'various' and *thermo* means 'heat'). These animals obtain most of their body heat from the sources outside their bodies; hence they are sometimes referred to as ectotherms. Examples of poikilothermic organisms include reptiles, amphibians and most fish. With exception of birds and mammals, most animals are ectotherms.

Animals that maintain a stable body temperature regardless of fluctuations in the environmental temperature are called homoiotherms or homoeotherms or homeotherms. Their heat is generated internally by metabolic activities; hence, they are also known as endotherms; and they include mammals and birds. The body temperature of endotherms ranges between 37 °C and 44 °C. The higher the body temperature, the greater the metabolic rate in the animal's body. For example, birds have higher metabolic rate to cater for the energy needed for flight. Their body temperature ranges between 38.5 °C and 44 °C. Homoeotherms can regulate their body temperature through negative feedback control. They control their body temperature independently of the environment; they use internal physiological control mechanisms as well as behavioural mechanisms.

Adaptation of endotherms to cold and hot climatic conditions

In order to survive in a variety of habitual environment, species of mammals have developed various physiological adaptive features or mechanisms. This diversity of living environment include the hot arid environment of the desert, the colder and glacial environment of the Arctic and Antarctic poles, the salty environment of the oceans, low oxygen environment of mountain peaks and the dark environments of the deep sea and oceans. Animals in the cold environment such as arctic fox have insulating layers with a thick coat of fur or thick layer of fat that help to reduce the rate of heat transfer thereby retaining body heat and keeping the animal's body temperature at constant level. Another strategy of cold weather used by some animals is a temporary decrease of metabolic rate and body temperature. This helps to decrease the temperature difference between the animal body and the environment thereby minimizing heat loss.

Other adaptations for survival of animals such as bears in the extreme cold climate include: hibernation during the cold period. The body temperature falls to a few degrees and an animal falls into a deep sleep. This tendency enables the animal to conserve energy.

In the hot and dry environment, endotherms develop cooling mechanism by means of evaporation of water across their respiratory surfaces or across the skin

through sweat glands. Animals with fur such as cattle, dogs, and birds have limited ability to sweat; therefore, they rely on panting to increase evaporation of water across the moist surface of their tongue and mouths.

Another adaptation to the hot environment is the possession of long loops of Henle of the kidney. This enables animals to produce super-concentrated urine that helps to conserve water. This tendency is common for the desert dwellers such as kangaroo rats, and camels. Most small animals with high surface area to volume ratio usually face major difficulties in overcoming high temperatures. Therefore, they remain in burrows during the day when it is hot and come out at night when it is cool. This nocturnal tendency enables small animals like rodents to survive in extremely hot climates. Some mammals that live in deserts have special adaptations in their kidneys and sweat glands that allow them to survive when only very small amounts of water are available to them.

Regulation of body temperature in endotherms

Endotherms have developed a variety of adaptive mechanisms for maintaining a constant or stable body temperature. The adaptation for balancing heat gain and heat loss may be anatomical, behavioural, or physiological. The process of controlling body temperature in endotherms falls under two homeostatic systems, namely regulation of skin temperature and regulation of the body core temperature, which includes vital organs of the body and the brain. The regulation of skin temperature involves four major components: the set point, detector, comparator or regulator, and corrective mechanism. First, the set point is the favourable skin temperature or the temperature at which an individual feels comfortable and relaxed. Second, the detectors are the thermo-receptors in the skin containing heat and cold receptors, which are responsible for detecting increase and decrease in the skin temperatures respectively. Third, the comparator is the cortex of the brain which is responsible for controlling conscious thoughts and feelings. Thus, if the affected individual feels too cold or too hot can decide to take appropriate action, either to move to a cooler or warmer place, remove or add more clothes or take other appropriate voluntary actions that may help to bring the skin temperature back to favourable state. The error signals are sent to voluntary skeletal muscles through nerve impulses. Fourth, corrective mechanisms are initiated through behavioural responses.

In regulating the body's core temperature, actions are involuntary, controlled by internal physiological responses. The set point of the homeostatic control mechanism is the mean body temperature (36.7 °C or 37 °C) which is genetically determined. In this system, the sensor and control centre for body temperature are located in a small part of the brain called the hypothalamus which is sensitive to temperature fluctuations. It possesses two thermoreceptors, namely the heat loss and heat gain centres. The heat loss centre is located in the anterior hypothalamus and is activated by increase in blood temperature; where as heat gain centre

is located in the posterior hypothalamus and is activated by decrease in blood temperature.

On the other hand, if the body core temperature rises to above 40 °C, the homeostatic control mechanism breaks down and positive feedback takes place. This causes a person to go into a state called hyperthermia. The patient experiences a very weak pulse rate, becomes excessively irrational, and sluggish. If the situation is not controlled, the patient may go into a coma and death may occur.

Maintenance of a constant body temperature in warm environments

When the environment is overheated, the animals use the following adaptive mechanisms to overcome the effects of overheating.

a) Vasodilation

This is an increase in the diameter of superficial blood vessels near the body surface caused by nerve signals, resulting into the relaxation of the vessel's walls. The blood in the capillaries in the skin may take three alternative routes; through capillaries close to the skin surface, in the dermis, and beneath the layer of subcutaneous fat. In warm climates, superficial arterioles dilate in order to allow blood flow close to the skin surface. Heat from the blood is rapidly conducted through the epidermis to the skin surface from where it is radiated away from the body. Rise in blood pressure within the capillaries cause them to dilate, that facilitate heat loss due to radiation, convection and conduction resulting into an increase of blood flow near to the skin surface. In cold environments, the blood flow in the body escapes the skin through the shunt vessels, resulting into reduction in heat loss. Just a small amount of blood passes into the skin to keep the tissue alive.

b) Sweating

Human beings have the ability to control body temperature through sweating because their skins are not covered by fur or feathers. They have sweat glands over the whole body that enable them to be more efficient at cooling through sweating. The human being can produce about 1000 ml of sweat per hour. Animals with fur have limited sweat glands which are confined to areas that do not have fur, for example pads of the feet in dogs and cats. Animals with feathers such as birds lack sweat glands. Their skins are covered by feathers which prevent evaporation through the skin (evaporation occurs from the surface of their lungs and air sacs).

c) Panting and licking

In animals with few or no sweat glands such as dogs and birds, cooling by evaporation takes place through the mouth and the nose. Dogs hang out their tongues; this may result in an increase of breathing rate and excessive removal of carbon dioxide from the blood thereby reducing heat from the body. Some animals lick their bodies to deposit saliva onto their body surfaces, which provide similar means of evaporative cooling. Licking is common to some animals that do not sweat, instead they make use of saliva to cool their bodies. For example; rabbits lick their front legs and chests, cats lick inside of their front paws and spread the

saliva across their ears and face, rats lick their testicle, and kangaroos lick their fore arms and wrists.

d) Use of body extremities

When compared to related species from cold climates, animals in warm climates usually have large extremities such as ears and large bushy tail. They are well supplied with blood vessels and covered by relatively short hairs, making them good radiators of heat.

e) Large surface area to volume ratio

Animals with a large surface area to volume ratio (relatively small animals) lose energy (temperature) faster than those with smaller surface to volume ratio. To compensate for this, small animals such as mice feed more frequently compared to large animals such as lions. The former animals also tend to utilize an energy - rich diet such as nuts rich in lipids.

f) Behavioural mechanisms

Many desert animals regulate their body temperature by using different behavioural mechanisms. For example, some animals such as mice and hedgehogs avoid heat by sheltering under the rocks or by burrowing in the soil during drought season. Others, like bat avoid hottest periods by being nocturnal, a tendency of being active during the night and inactive during the day. This minimises the rate of body metabolic activities during the day and increases at night. Some animals like rodent, ground squirrels and bears hibernate during cold temperatures. Hibernation is the behavioural state where by an animal becomes inactive, both during the day and at night. This tendency usually takes place during winter season, which sometimes is referred to as winter dormancy.

Winter dormancy is associated with reduced body metabolic rate, low body temperatures, slow breathing and low heartbeat rate. The animal appears to be in a deep sleep for several days, weeks or months depending on the species. This helps to conserve energy, especially during winter when food is scarce. Before entering hibernation, most animals eat a large amount of food and store energy in fat deposits to survive the winter. Hibernation can also take place during the hottest period or summer. This state is called aestivation or summer dormancy. Some animal species that aestivate include reptiles. The arousal of an animal from hibernation state usually occurs spontaneously. It is driven by some internal mechanisms. External stimuli often fail to wake the hibernating or aestivating animal, making it subject to predation if it is discovered by its enemies.

g) Insulation

This is provided by a layer of fur or fat that protects or blubs the body against changes in the environmental temperature. The thick coat of fur is called insulator while the thick layer of fat is called blubber. The insulator or blubber layer helps retain body heat and keeps the animal's body temperature constant. Animals in the warm climates usually have fur with light colours to enhance sun rays' reflection and thereby minimising heat gain and accelerating heat loss from the body. During this process, the hair erector muscles in the skin are relaxed and the fur

lies close to the skin surface. This causes the thickness of insulating warm hair to be reduced, and therefore, the body heat is readily dispersed.

Maintenance of a constant body temperature in cold climates

Endotherms living in cold environment and those in hot climates experiencing cold weather have the following adaptations which enable them to maintain constant body temperatures:

a) Vasoconstriction

When the animal is subjected to cold conditions, the superficial arterioles are constricted. This reduces the quantity of blood reaching the skin surface. Much blood passes beneath the insulating layer of subcutaneous fat; therefore, little heat is lost to the outside.

b) Shivering

In cold conditions, the skeletal muscles of the body may undergo rhythmic involuntary contractions which increase the amount of heat produced in the body.

c) Insulation

It is achieved by an external covering of fur or feathers and or an internal layer of subcutaneous fat. Their thickness is related to the intensity of coldness to that environment. It is an effective means of reducing heat loss from the body.

d) Increased metabolic rate

During cold conditions, the liver increases its metabolic rate. There is also increased activity of the adrenal, thyroid, and pituitary glands resulting into secretion of hormones that help to increase the body metabolic rate; hence, additional heat is produced in the body. The increased metabolic rate of the body requires increased food consumption; that is why animals feed on large amount of food in cold climates.

Temperature regulation by ectotherms

Ectotherms regulate their body temperature mainly by behavioural means, depending on external heat sources; since these organisms do not have temperature control center like endotherms. The exchange is controlled by three factors which are; radiation, conduction and flow. Their body temperature rises and falls along with the temperature of the surrounding environment. Although they generate metabolic heat like endotherms, they cannot increase heat production to maintain an internal body temperature. Most of the adjustment mechanisms are by behavioural means such as: huddling, hibernation, burrowing, aestivation, clustering, migration, and exposing themselves to the sun in hot environment.

a) Huddling

In cold regions, animals are usually active during the day. Huddling of individuals is also another common way of reducing heat loss. Some animals are able to crowd together in a tightly packed group to keep them warm and reduce much heat loss when an individual animal is exposed to cold open air.Therefore, this is also a means of conserving heat.

b) Hibernation

Some animals in cold climates undergo a period of long sleep. During this time, the metabolic rate is reduced 20-100

times below normal which consequently reduces food and oxygen utilisation.

c) Sun basking

Ectothermic animals may use radiant heat provided by the environment to warm their bodies. Solar radiation is the most common way, as many ectotherms use the sun's rays to warm up their bodies. Reptiles and some amphibians bask in the sun with their bodies spread out to increase the surface area for heat absorption. When it is too hot, they hide in the shade or near water bodies; allowing their bodies to cool.

d) Clustering

Some animals exhibit group behavioral mechanisms to regulate their body temperatures. A good example is how honey bees cuddle together in large groups to retain and generate heat. A similar example is how some gregarious caterpillars bask in the sun in large groups to gather heat.

e) Burrowing

Some ectotherms burrow themselves and hide deep in the ground. This helps them to survive in cold environments.

f) Aestivation

Some ectothermic animals like earthworms, snails, frogs, crocodiles, lizards, and tortoise maintain their body temperature by reducing body metabolic activities and protecting themselves from very high temperature. During summer time, some animals usually tend to rest in shady or cool places. Normally, they take a sleep during the hot hours of daytime as a means of avoiding environmental stress.

Some ectotherms have developed some chemical processes to survive the cold. These animals, such as chorus frogs, and gray tree frogs endure the cold by undergoing chemical changes to prevent their tissues from freezing. Other animals such as wood frog can tolerate and regulate a frozen state by changing the chemical composition of their blood to a sugary state that helps them avoid freezing.

Exercise 7.2

1. Explain the mechanisms of temperature regulation in endothermic organism.
2. Show the role of the hypothalamus in temperature regulation.
3. Describe the adaptations of mammal to cold and hot climatic conditions.

7.3 Excretion

The maintenance of homeostasis in animals involves osmoregulation or balancing the levels of water and salt in the body. It also involves the removal of metabolic wastes from the body through excretion; the process by which metabolic waste is eliminated from an organism's body. In vertebrates, this is primarily carried out by the lungs, kidneys and skin.

Significance of excretion

It is important that living organisms must get rid of excretory wastes from their bodies, because the removal of wastes prevents unbalanced body's chemical equilibria. Moreover, it is a means for removal of toxic wastes which, if allowed

to accumulate, inhibit action of many enzymes involved in metabolic pathways. Consequently, this will lead to failure in many physiological processes. Excretion also helps to regulate water content of the body fluids. Excretory nitrogenous wastes are removed from the bodies of living organisms in a form which is determined by the availability of water. The pH of blood is regulated by excretion. For example, organisms tend to excrete ions such as hydrogen ions (H^+) and hydrogen carbonate ions (HCO_3^-) which have major influence on pH.

Major excretory products in animals

The major excretory products in animals are nitrogenous compounds such as urea, ammonia, and uric acid from breakdown of proteins and nucleic acids, carbon dioxide from cellular respiration and bile pigments from breaking down of worn out red blood cells in the liver.

Nitrogenous waste products

Breakdown of nitrogen containing molecules such as amino acids results in excess nitrogen that must be removed from the body. When amino acids are broken down by the body to generate energy or converted into fats or carbohydrates, the amino (NH_2) group must be removed because they are not needed, and they may be toxic. This excess nitrogen may be excreted in the form of ammonia, urea, or uric acid.

Ammonia. Ammonia is quite toxic and highly soluble; hence it can be a nitrogenous excretory product if sufficient water is available to wash it from the body. It is excreted by most fish and other aquatic animals whose gills or body surface are in direct contact with water. These animals are called ammonotelic.

Urea. Animals like sharks, adult amphibians, and mammals usually excrete urea as their nitrogenous waste. Urea is a much less toxic, and less soluble than ammonia. It can be excreted in a moderately concentrated solution. This elimination strategy allows body water to be conserved, an important advantage for terrestrial animals with limited access to water. The animals in this group are termed as ureotelic.

Uric acid. Uric acid is not toxic and it is insoluble in water. Poor solubility is an advantage if water conservation is needed. Uric acid can be concentrated even more readily than urea can. Uric acid is usually excreted by insects, reptiles, and birds, these are collectively termed as uricotelic animals.

Kidney position, structure and functions in human body

Kidneys are paired bean-shaped organs found on each side of the back of the lower portion of the abdominal cavity (Figure 7.5). The larger left kidney is located a bit higher than the right kidney. Unlike other organs found in the abdomen, kidneys are located behind the lining (peritoneum) of the abdominal cavity. Thus, they are considered retroperitoneal organs. These bean-shaped organs are protected by the back muscles and the ribs as well as the fat (adipose tissue) that surrounds them like a protective padding. Located above each kidney is an adrenal gland which secretes adrenaline hormone. For each kidney, the

renal artery supplies blood which a renal vein returns to the vena cava. The ureter removes urine produced by the kidney, transfering it to the urinary bladder for temporary storage, before being released through the urethra. The exit from the bladder is controlled by a sphincter (a ring of muscles).

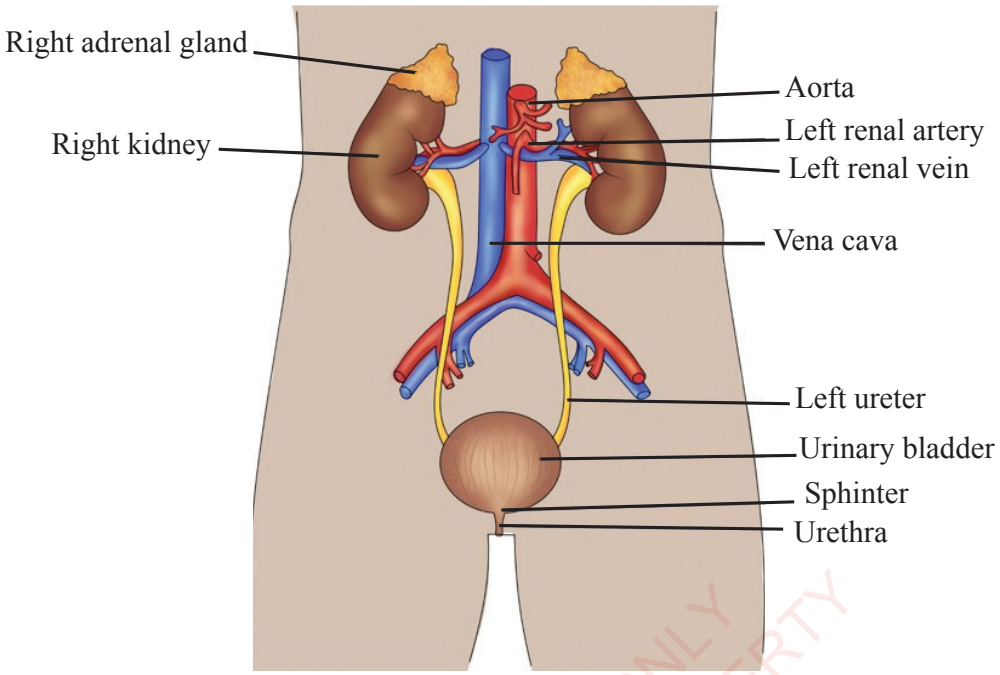


Figure 7.5 Human urinary system

The bean-shaped kidneys have an outer convex side and an inner concave side called the renal hilus. A transverse section (T.S) of the kidney reveals an outer part called cortex and an inner part called medulla. A thin connective tissue called fibrous capsule surrounds each kidney. This capsule maintains the kidneys' shape and protects the inner tissues. The cortex contains parts of the nephrons, glomeruli and capsule, while the medulla contains tubular part of the nephrons and blood vessels, forming the renal pyramids which project into the pelvis, leading to the ureter. Kidneys are well supplied by blood vessels, forming a network of blood capillaries (Figure 7.6).

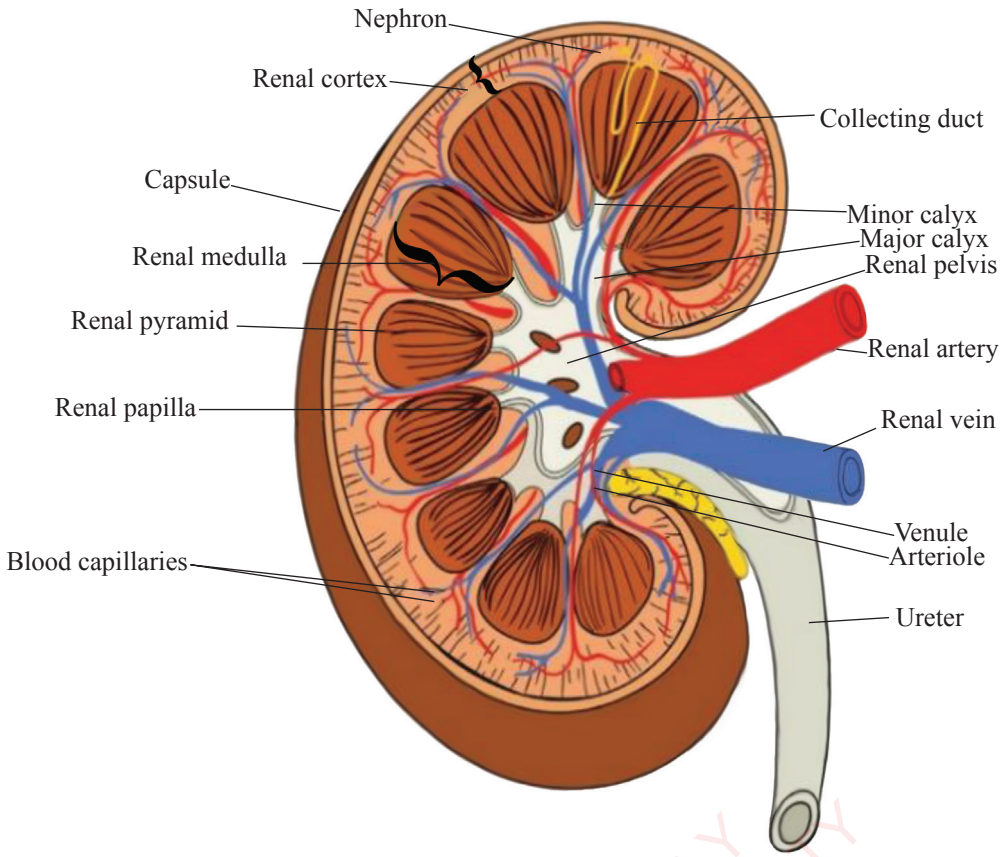


Figure 7.6 Transverse section through the mammalian kidney

General functions of the kidneys

Kidneys are multifunctional organs, some core functions of the kidneys include:

a) Excretion

Kidneys filter out toxins, excess salts, and nitrogenous wastes created by cell metabolisms. Urea is synthesised in the liver and transported through the blood to the kidneys for removal in urine.

b) Water balance

As kidneys are key in the chemical breakdown of urine, they react to changes in the body's water level every minute. As water intake decreases, the kidneys adjust accordingly and leave water in the body instead of helping to excrete it.

c) Blood pressure regulation

The kidneys need constant pressure to filter the blood. When it drops too low, the kidneys increase the pressure. One way is by producing a blood vessel constricting protein, angiotensin, which also signals the body to retain sodium and water. Both constriction and retention help restore normal blood pressure.

d) Red blood cell regulation

When the kidneys do not get enough oxygen, they send out a distress call in the form of erythropoietin; a hormone that stimulates the bone marrow to produce more red blood cells. This process is called erythropoiesis.

Table 7.1 Summary of parts of the kidney and their functions

Parts of the kidney	Description
Renal hilus	An indentation near the centre of the concavity of the kidney where the renal vein and ureter leave the kidney and the renal artery enters the kidney.
Renal capsule	A tough, fibrous membrane, surrounding the kidney. It consists of dense, irregular connective tissues which protect and help to maintain the kidney's shape. It is also surrounded by fatty tissue which helps to protect the kidney from damage.
Renal cortex	The outer reddish part of the kidney that has a smooth texture; it is where the Bowman's capsule, glomeruli, proximal and distal convoluted tubules and blood vessels are found.
Renal medulla	The inner striated red-brown part of the kidney.
Renal pyramids	Stripped, and triangular in structure within the medulla, which are made of straight tubules and corresponding blood vessels.
Renal pelvis	The funnel-shaped cavity that receives urine drained from the nephrons through the collecting ducts and papillary ducts.
Renal artery	The blood vessel that delivers oxygen- rich blood to the kidney; it enters the kidney through the hilus and divides into smaller arteries, which separate into afferent arterioles that serve each of the nephrons.
Renal vein	The blood vessel that receives deoxygenated blood from the kidney and returns it to the systemic circulation.
Afferent arteriole	The blood vessel that delivers oxygen-rich blood to the glomerulus under high pressure.
Efferent arteriole	The blood vessel that receives oxygenated blood from the glomerulus.
Kidney nephrons	The functional units where the kidney's main functions are performed: There are about a million nephrons in each kidney.
Collecting duct	This part of the kidney nephron collects urine and drains into papillary ducts, minor calyx, and major calyx, and finally into the ureter and urinary bladder.
Ureter	The tubular structure which conveys urine from the pelvis of the kidney to the urinary bladder.

e) Regulation of pH of the blood

Kidneys excrete hydrogen ions into urine. At the same time, they conserve bicarbonate ions which are an important buffer of hydrogen ions.

f) Regulation of the ionic composition of blood

Kidneys regulate the quantities of ions in the blood. Important examples of ions whose quantities are regulated by the kidneys include sodium, potassium, calcium, chloride and phosphate ions.

g) Synthesis of vitamin D

Kidneys are involved in the synthesis of calciferol, which is an active form of vitamin D.

The nephron

The nephron is the kidney's functional unit that is involved in production of urine in the process of removing waste and excess substances from the blood. Generally nephron is responsible for the filtration, excretion and re-absorption of most of the water and other materials. Each kidney has more than a million nephrons in the renal cortex, which gives it a granular appearance on sagittal section (Figure 7.7). Nephrons are used to separate water, ions and small molecules from the blood molecule, and filter out wastes and toxic materials, then it selectively returns the needed molecules to the blood. The most primitive nephrons (pronephros) are found in the kidneys of primitive fish, amphibian larvae, and embryos of more advanced vertebrates. The nephrons found in the kidneys of amphibians and most fish, and in the late embryonic development of more advanced vertebrates, are only slightly more advanced in structure (mesonephros). The most advanced nephrons occur in the adult kidneys, or metanephros of land vertebrates, such as reptiles, birds, and mammals.

There are two types of nephrons, namely cortical nephrons, (which are found deep in the renal cortex) and the juxtamedullary nephrons, which make up about 15 percent of total nephrons and lie close to the medulla. The nephrons consist of a renal corpuscle, a tubule, and a capillary network. These originate from the small cortical arteries. Each renal corpuscle is composed of a glomerulus (a network of capillaries) and a Bowman's capsule (the cup- shaped chamber that surrounds it). The Bowman's capsule connects to a long convoluted renal tubule which is divided into three functional parts. These consist of the proximal convoluted tubule, the loop of Henle (nephritic loop) with its descending and ascending limbs, and the distal convoluted tubule, which empties into the collecting ducts.

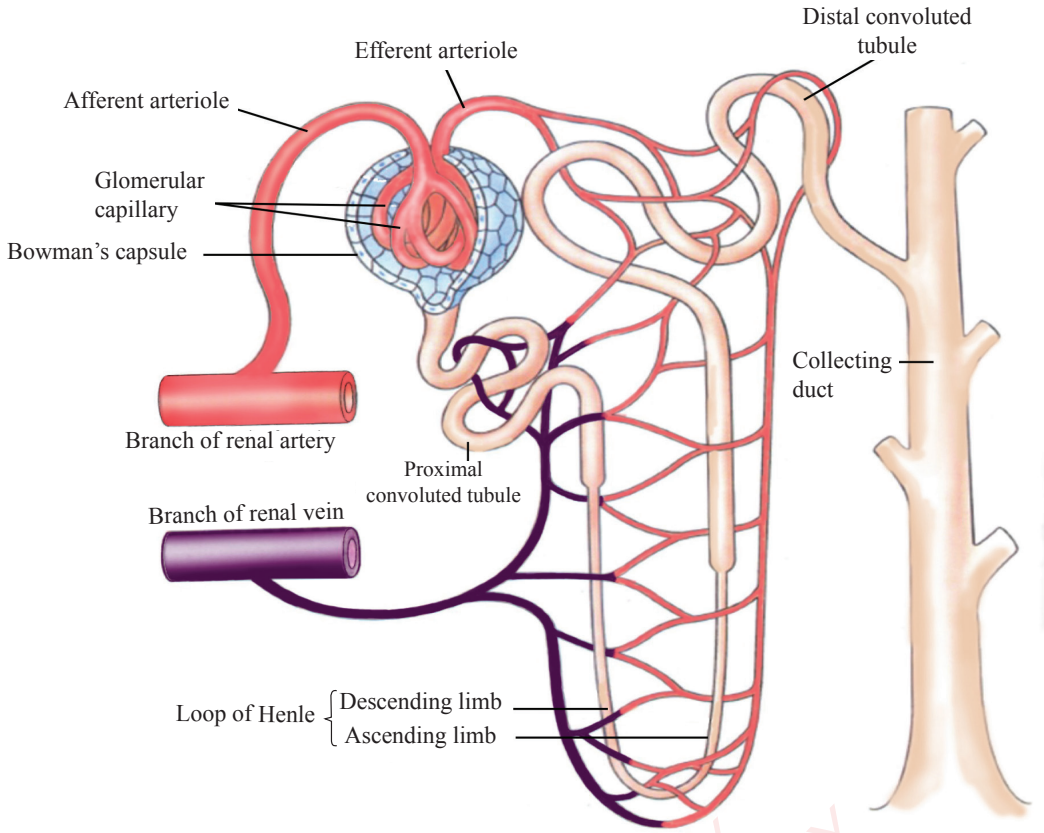


Figure 7.7 Structure of the mammalian nephron

The collecting ducts fuse together and enter the papillae of the renal medulla.

Urine passes through the renal medulla as a fluid with high sodium content and leaves through the renal papillae, into the renal calyces, the renal pelvis, and the bladder through the ureter.

The outer layer of the Bowman's capsule is composed of squamous epithelial cells. The inner layer is composed of specialised cells that allow easy passage of molecules, and the glomerulus consists of endothelial cells with fenestrae (pores). The renal corpuscle acts as an ultra-filtration unit, filtering the blood and separating the larger particles (which stay in the blood vessels) from the small ones (which pass into the renal tubule). Therefore, it is a site for ultra-filtration; that is pressure filtration. This pressure is known as hydrostatic pressure, and it stems from blood pressure. Thus, the blood brought into the glomerular capillaries by the afferent arteriole is pumped by the heart at high pressure; which rises as the blood leaves the wide arteriole and enters the narrow capillaries.

The structures of the glomerulus and Bowman's capsule is adapted for filtration in that, endothelial layers of glomerulus are very thin and have many pores to allow the passage of a glomerular filtrate. A network of fibres such as collagen

fibres, with spaces between them, allows the passage of small solute molecules in the filtrate. They restrict the passage of blood cells that are larger than the pores. Large molecules such as proteins are also restricted from passing through and are repelled by the negatively charged fibres. Moreover, the epithelial layer of the Bowman's capsule contains podocytes, the highly modified filtration cells. These have extensions which interact to form filtration slits or pores to allow the passage of the glomerular filtrate.

The proximal convoluted tubule are mainly concerned with selective reabsorption so that valuable substances such as glucose are taken back to the blood but not lost in the urine. The cells of the proximal convoluted tubule are adapted for re-absorption as follows:

a) They have numerous microvilli and basal channels which increase the surface area for the absorption process.

b) They have numerous mitochondria to supply energy which is constantly needed for active uptake of substances from the filtrate.

c) Their basement membranes are very close to the endothelial lining of blood capillaries to ensure fast uptake and efficient transportation of the reabsorbed substances back into the body.

d) Channel proteins are present for transportation of substances like amino acids and ions from the cells of the proximal convoluted tubule, to the spaces between these cells and the basal channels.

e) At the base of the microvilli, small proteins from the renal fluid are removed by the process of pinocytosis. The proteins are then enclosed in pinocytic vesicles and are finally broken down by hydrolytic enzymes from the lysosomes (Figure 7.8).

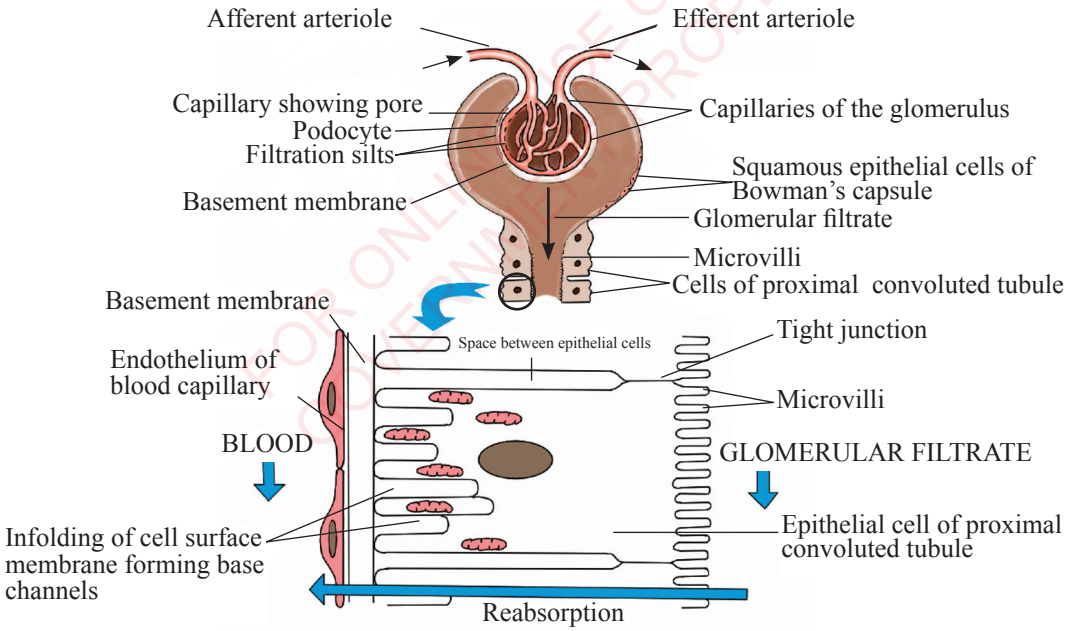


Figure 7.8 Structure and function of renal corpuscle and proximal convoluted tubule

The loop of Henle acts as a counter current exchange mechanism creating a low water potential (high solute content) in the medulla of the kidney so that water can be reabsorbed by osmosis. The descending limb has a thin membrane which is freely permeable to water and impermeable to salts and urea. The thick ascending limb has numerous mitochondria which provide energy for active uptake of sodium chloride and other ions from the renal fluids back into the interstitial regions of the medulla.

The distal convoluted tubule and collecting ducts are concerned with osmoregulation; varying the amount of water reabsorbed into the blood. The cells of the distal convoluted tubule have a similar structure to those of the proximal convoluted tubule, with microvilli lining the inner surfaces to increase the surface area for absorption, and numerous mitochondria to supply energy for active transport.

Formation of urea in mammals

Urea is the nitrogenous waste product of humans and other land living mammals. The body is unable to store excess amino acids taken in the diet. Those not immediately needed for protein synthesis or making sugar must be removed by the process called deamination, which is followed by urea formation in the liver cells. The process of urea formation occurs in the urea cycle which is also called ornithine cycle (Figure 7.9) and involves the following stages:

a) Formation of carbamoyl phosphate

Before the cycle, ammonia (NH_3) from metabolism of nitrogen containing compounds combine with carbon dioxide (CO_2) gas from respiration in a solution form (ammonium ions and bicarbonate ions respectively) resulting into the formation of carbamoyl phosphate, by the help of the enzyme carbamoyl phosphate synthetase-I. The reaction occurs in the mitochondria of the liver cells, and requires 2 ATP molecules.

b) Synthesis of citrulline

The carbamoyl phosphate formed in the first step enters the ornithine cycle and combine with ornithine resulting in the synthesis of citrulline, aided by an enzyme citrulline synthase or ornithine transcarbamoylase. In the reaction the phosphate group is released. Citrulline can easily pass through the mitochondrial membrane, thus it diffuses from the mitochondrion into cytosol (cytoplasm) of liver cells.

c) Synthesis of argininosuccinate

In the cytosol, citrulline combines with the amino group of aspartate under condensation reaction catalyzed by enzyme argininosuccinate synthetase to form argininosuccinate. It requires ATP which is hydrolysed to adenosine monophosphate (AMP) resulting in the utilization of two high energy bonds. Magnesium ions (Mg^{2+}) act as cofactors. This reaction incorporates the second nitrogen from aspartate.

d) Cleavage of argininosuccinate

The cleavage of arginisuccinate involves the enzyme argininosuccinase, an intermediate enzyme in the urea synthesis pathway whose function is imperative to the continuation of the cycle. It acts

reversibly to cleave argininosuccinate into a free arginine and fumarate. The arginine continues with the cycle in the other stage, whereas fumarate enters the Tricarboxylic Acid (TCA) cycle, which is also known as Kreb's cycle. The linkage between TCA cycle and urea cycle is known as the Kreb's bi- cycle.

e) Cleavage of arginine

Arginine is hydrolysed into ornithine and urea under the influence of the enzyme arginase; hence, arginine is known as a semi-essential amino acid. Though it is synthesised in the body, it is not available for protein synthesis. Ornithine is regenerated in this step and the urea cycle completes by the formation of urea. The ornithine produced is transported back to the mitochondria to start the cycle again while urea is transported to the kidney through blood vessels to be excreted. Thus the urea cycle brings two amino groups (NH_2) and hydrogen carbonate ions (HCO_3^-) together to form urea.

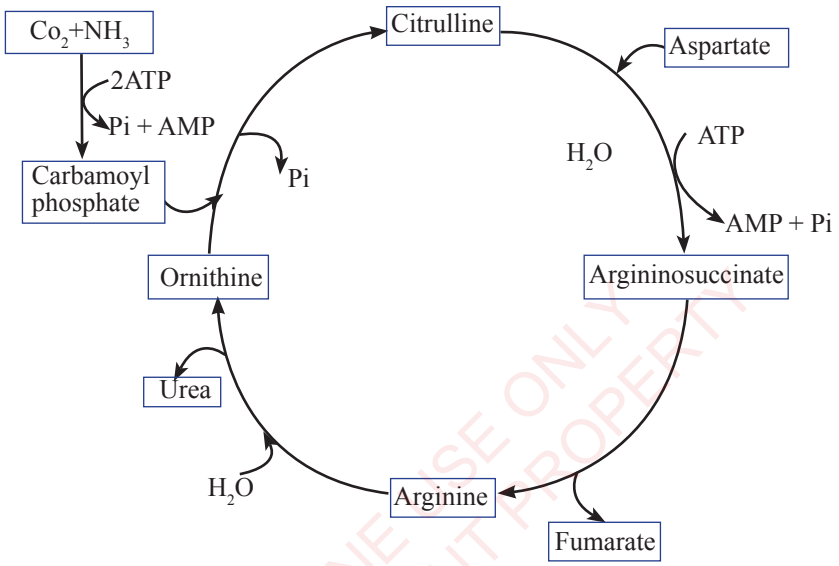


Figure 7.9 The Ornithine cycle

Urinary disorders in human

The urinary tract consists of the kidneys, ureters, bladder and urethra. Urinary disorders include any infections or conditions that affect any of these parts of the urinary system or their functions. The following are some of the common urinary disorders in human beings:

a) Uremia

This condition results from toxic effects of abnormally high concentrations of urea in the blood resulting into kidneys' failure to expel it via urine. The end products of protein metabolism accumulate in the blood but are normally filtered out when the blood passes through the kidneys. However, urea accumulation in the blood is comparatively high in uremia victims. In such patients, urea can be removed by the process called haemodialysis. However, there are still some complications that affect people on

dialysis such as cardiovascular problems and severe itching from the imbalance of minerals in the body.

b) Renal failure (RF) or kidney failure

Renal failure is a decrease or cessation of glomerular filtration in humans (it is a partial or complete loss of kidney function). Kidney failure can be either acute or chronic. In acute renal failure (ARF), both kidneys abruptly stop working. The main feature of ARF is either oligouria (scanty urine production) in which the daily urine output is less than 250 ml or anuria in which daily urine output is less than 50 ml. The causes of renal failure may be low blood volume (atherosclerosis), decreased cardiac output, damaged renal tubules, kidney stones, nephritis, and some excessive use of antibiotics. The effect of renal failure includes oedema, that is accumulation of excess fluids in various parts of the body which results into swelling of legs. Also, the potassium level rises, leading to failure to produce enough erythropoietin for adequate red blood cells production, hence anaemia.

c) Kidney stones (renal calculi)

Concentration of mineral and organic matter that forms in the kidneys results into small particles called stones. These may become too large, hence impairing the normal renal function. Urine contains many salts in solution. If the concentration of these mineral salts becomes excessive, the excess salts precipitate as crystals that may enlarge to become visible solid particles called stones. Such stones give rise to severe colic pain starting in the back and radiating down to the front of the thigh or the testicle or vulva on that side. The best way to prevent most kidney stones is to drink enough fluids every day.

d) Urinary tract infections (UTI)

In humans, UTI is caused by the invasion of microorganisms, usually bacteria, into the urethra and bladder. The most common UTI cases that affect the bladder and urethra are:

Infection of the bladder (cystitis). This type of UTI is usually caused by bacteria, normally *Escherichia coli* (*E. coli*); a type of bacteria commonly found in the gastrointestinal tract (GIT). All women are at risk of cystitis because of their anatomy, specifically the short distance from the urethra to the anus and the urethral opening to the bladder.

Infection of the urethra (urethritis). This type of UTI can occur when GIT bacteria spread from the anus to the urethra. Also, because the female urethra is close to the vagina, sexually transmitted infections such as herpes, gonorrhea, chlamydia and mycoplasma can cause urethritis.

The infection of the urinary tract can result into either minor or major illnesses. For example, an attack of cystitis-inflammation of the bladder may cause only minor illness. The attack of the renal system is characterised by frequent and painful urination. Other complications involve: recurrent infections; especially in women who experience twice or more UTI cases in a six-month period within a year and permanent kidney damage from twice acute or chronic kidney infection (pyelonephritis) due to an untreated UTI.

Likewise, pregnant women get a risk of delivering low birth weight or premature infants, whereas men experience urethral narrowing (stricture).

The preventive measures include: drinking plenty of liquids especially water so as to dilute urine and ensure frequent urination hence, allowing bacteria to be flushed from the urinary tract. Also, women are advised to wipe from front to back after urinating and after defecating so as to prevent the spread of bacteria from anal region to the vagina and urethra. Furthermore, a patient should seek medical advice from a recognised health centre or hospital.

e) Urinary tract obstruction

This is due to blockage or constriction at any point in the urinary tract. This impedes the normal flow of urine and causes urine to be retained in the bladder or kidneys. Obstruction causes urine to become blocked up into the kidneys, the condition is known as hydronephrosis. Obstructions in the urinary tract causes distension of the walls of the bladder, ureter, urethra, and kidneys. This condition may stem from Sexually Transmitted Diseases (STDs) such as syphilis and gonorrhoea. Its preventive measures include prevention against STDs and seeking for medical assistance whenever sensing signs of STDs.

f) Diabetes insipidus (DI)

The term diabetes insipidus is made up of two words; *diabetes,* which means 'overflow', and *insipidus* which means 'tasteless'. From this basic implication, diabetes insipidus means excessive production of very dilute urine. It is caused by deficiency of vasopressin hormone which is released by the posterior lobe of the pituitary gland. The vasopressin or antidiuretic hormone (ADH) facilitates reabsorption of water by the distal convoluted tubule and the collecting duct of the nephrons. Therefore, lack of this hormone implies that much water remains in renal fluid; therefore, it is lost through urine. The symptoms of diabetes insipidus include excessive dilute urine, intense thirst, and tiredness. Regular physical exercises and healthy eating may prevent an individual from getting diabetes. Diabetic patients are advised to go to the health centre or hospital for medical advice and proper treatment.

Exercise 7.3

1. Analyse the major excretory products in vertebrates.
2. Describe the structure of the mammalian nephron.
3. Explain three common disorders of the urinary system in human.
4. How does the type of nitrogenous wastes excreted by an animal relate to water availability in its body?
5. Describe the mechanism of urine formation.

7.4 Osmoregulation

In most vertebrates, kidneys are the most important organs involved in osmoregulation. The kidneys perform several functions critical to homeostasis. Such functions include maintaining the balance between water and various types of salts. This is important because ions such as Na^+, Ca^{2+}, and K^+ greatly affect the functioning of the body systems such as the skeletal, nervous and muscular systems. The kidneys produce urine; a liquid that contains a number of different metabolic wastes. The concentration of urine produced by an animal varies depending on the environment as well as on the factors, such as water and salt intake. The process of maintaining constant body's osmotic condition is called osmoregulation. It is concerned with the regulation of water and solute concentration of the body fluids.

Osmoregulation in marine elasmobranches

Marine elasmobranches are cartilaginous fish such as sharks, rays, and skates. They live in sea water whose salt concentrations are higher than those of their body fluids. Due to this difference in concentrations, the fishes tend to lose water from their bodies into the sea. To overcome this problem, the marine elasmobranches have developed mechanisms of making their body fluids less hypotonic to sea water. Because of this, the animals face another problem of a natural and continuous diffusion of water into their bodies from their surrounding sea water. To overcome these problems and to make their body fluids isotonic to sea water, such fishes have developed the following adaptations:

a) They have rectal glands which secrete salts to increase their osmotic pressure. This mechanism aims at balancing the internal osmotic pressure to that of the surrounding sea water.

b) They retain nitrogenous waste chemicals, such as urea, and trimethylamine oxide (TMAO) in their body cells. These chemicals are kept in high concentrations, and they change the diffusion gradient enabling a fish to absorb water instead of ingesting it. Despite the fact that these are waste products and may be harmful to the animals at high concentrations, the marine elasmobranches have been able to produce and retain urea because their gills are impermeable to it. Their renal tubules in the kidneys are capable of reabsorbing urea from the renal fluid back to body cells. In addition, their cells are immune to the effects of high concentrations of urea.

Osmoregulation in mammals

An important evolutionary adaptation that allowed animals to survive on land was the development of a kidney that would produce concentrated (hypertonic) urine. The need for water conservation is particularly well illustrated in desert mammals such as the kangaroo rat. A major adaptation that allows the kangaroo rat to conserve water is the ability to form very hypertonic urine twenty times more concentrated than its blood plasma. The kidneys of the Kangaroo rat are able to accomplish this because the loop of Henle of their nephrons is much longer and more efficient than that of most other mammals.

Terrestrial mammals need to drink water at least occasionally to compensate for the water lost from the skin and respiratory passages and through urination.

Counter current multiplier

In the loop of Henle, a counter current exchange mechanism is combined with the active secretion of solutes. A system that uses this combined type of exchange is called counter current multiplier system. The loop of Henle functions as a counter current multiplier due to its close proximity of ascending and descending limbs, permeability of the descending limb to water, impermeability of the descending limb to solute, permeability of the ascending limb to solute, passive transport of solute in thin ascending limb, and active transport mechanism for the thick ascending limb (Figure 7.10). These features enable the loop of Henle to create a very high concentration gradient between the tissue fluid and blood in the medulla of the kidney and the urine in the collecting ducts. The loop of Henle is connected at one end to the proximal convoluted tubule and at the other end to the distal convoluted tubule. It first descends deep into the medulla and then bends and ascends into the cortex again. Throughout its length, it is surrounded by fine looped blood vessels called the Vasa recta. These vessels carry blood from the glomerulus to the renal vein.

Salts like sodium and chloride ions, diffuse passively out of the thin ascending limb and pumped actively out of the thick ascending limb into the surrounding tissue fluids. This pumping of salts out of the limb creates an osmotic gradient which draws water out of the descending limb into the medulla. This is because the ascending limb is impermeable to water; therefore, water moves out of the limb only to the descending limb. When water in the descending limb is pumped out, it causes the fluid in the descending limb to have a slightly higher salt concentration compared to the ascending limb. The process continues down the length of the loop so that this concentration effect is multiplied. The counter current multiplier means that the fluid in and around the loop of Henle becomes saltier as it goes down the loop, and it is saltiest at the bottom end of the loop. In contrast, it becomes less salty as it goes up the ascending limb Therefore, the final salt concentration depends on the length of the loop, the longer the loop; the higher the final salt concentration in the tissues.

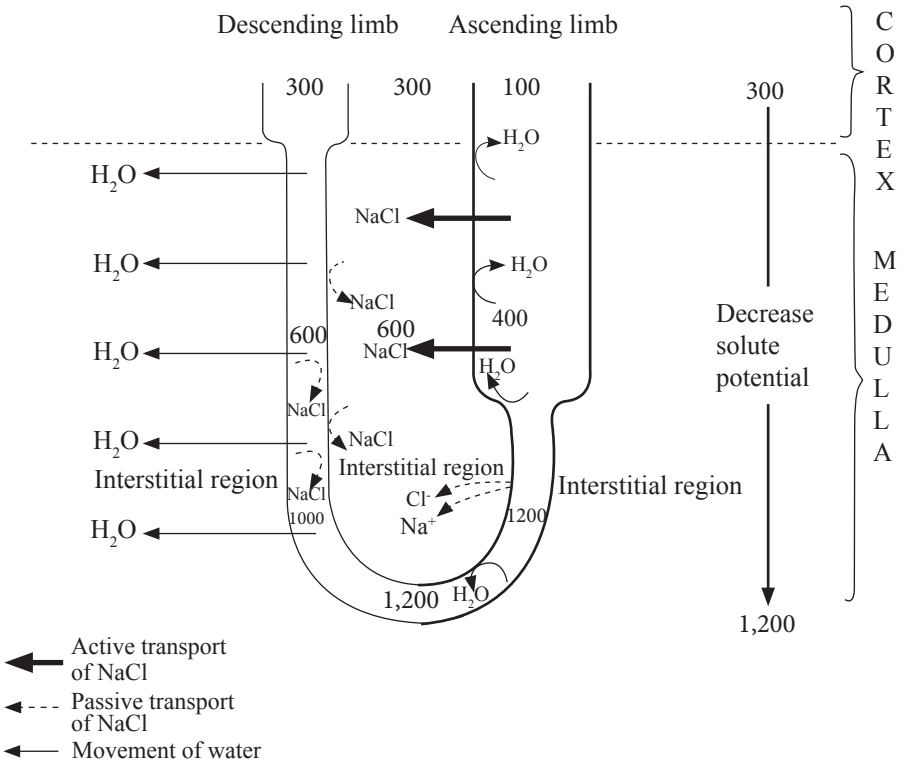


Figure 7.10 Counter-current multiplier system of the loop of Henle

Hormonal control of osmoregulation

As water moves in the loop of Henle, it leaves the loop of Henle with the water potential greater than that of blood plasma. This creates a concentration gradient between fluid in the distal convoluted tubule and the surrounding tissue fluid. The concentration gradient is enhanced when salts are actively pumped out of the distal convoluted tubule. Reabsorption of water in the distal convoluted tubule and the collecting duct will depend on their permeability, which is controlled by the hormone called Antidiuretic hormone (ADH). This hormone is released by the posterior lobe of the pituitary gland in response to an increased concentration of salts in the blood. When ADH is present, more water is reabsorbed (blood volume and pressure rises) and the urine produced is more concentrated.

The regulation of salt and blood pressure are closely connected. If the sodium ion concentration in the blood is low, the blood water potential increases and water moves by osmosis into the tissue, slightly lowering the blood pressure. When blood pressure is not sufficient (below the set point), secretory cells near the glomerulus, juxtaglomerular apparatus secrete, renin. The later is an enzyme that changes angiotensinogen (angiotensinogen is a large plasma protein produced by the liver) into Angiotensin I. Later Angiotensin I is converted to Angiotensin II. When Angiotensin II reaches the adrenal cortex, it stimulates the secretion of aldosterone.

This hormone promotes the excretion of potassium ions and the reabsorption of sodium ions at the distal convoluted tubules. The reabsorption of sodium ions is followed by the reabsorption of water. Therefore, blood volume and blood pressure increase.

Adaptations of mammals to arid and semi-arid conditions

High temperature and low rainfall characterise some areas of this world. It becomes hard to believe that animals can survive in arid and semi-arid conditions. However, these animals survive because they have adaptations that allow them to live in the hot, dry conditions. These adaptations help to balance thermoregulation with water gain and loss. For instance, many mammals that live in the desert obtain much or all of their water from the food they consume. The reduced water intake is partially balanced through concentrated urine and dry faeces. Evaporative cooling helps to regulate temperature.

To limit the water loss through evaporative cooling, some mammals are nocturnal; have light coloration and other body features to help them dissipate heat and use micro-environments to reduce heat gain. This is only a short list of the many amazing adaptations. Characteristically, arid regions receive 100-250 mm of rain a year and semi-arid regions receive 250-500 mm of rain per year. The following are some of adaptations of mammals to the life in arid or semi-arid conditions:

a) Water and food consumption

Human beings obtain about 60% of the water they need from the ingested liquids, 30% from ingested food, and 10% from metabolism. Rodents and camels adapted to arid conditions obtain approximately 90% of water from metabolism and 10% from ingested food.

b) Excretory adaptations

The ability to excrete concentrated urine and dry feaces is an important adaptation to arid conditions. Mammals that are adapted to the desert have very long loop of Henle compared to animals that live in less arid regions and in aquatic environments. A longer loop of Henle allows urine to become very concentrated due to osmotic gradients in the kidneys. Desert rodents produce concentrated urine about five times as that of humans. Longer loop of Henle increases the efficiency of water reabsorption and hence a means for conserving water.

c) Behavioural adaptations

Behavioural adaptations are used to reduce the amount of heat gained by animals. Therefore, they reduce the need for evaporative cooling. One basic behavioural adaptation is the timing of activity rhythms. Nocturnal animals are able to regulate their heat load by resting during the day, since night-time temperatures can be 15-20 °C lower than the daytime. Examples of nocturnal animals include the quoll, bilby, and the spinifex hopping mouse.

Burrows are another type of microenvironment that is used by smaller mammals. In Arizona burrow temperature of a round-tailed ground squirrel was recorded. The air temperature was 40 °C and the soil surface was 70 °C but the burrow temperature did not exceed 29 °C. Many burrows are at a depth where evaporative cooling is not needed; it does not get hot enough in the burrows to require this technique.

d) Torpor and metabolic rate

Many mammals such as rodents and squirrels enter a period of torpor in response to severe heat. This is a period when metabolism decreases, the heart beat and respiratory system slows down based on a circadian rhythm. Torpor can be considered as a water conserving mechanism because the animal's body temperature is lowered and it does not have to rely heavily on evaporation. If the period of torpor becomes longer, it is called aestivation or summer dormancy.

Aestivation allows an animal to survive when there are high temperatures and a scarcity of water and or food. An aestivating animal can live longer with its energy reserves due to lowered metabolism. Moreover, there is a reduced water loss through lowered breath rates. Metabolic rates are lower during torpor and aestivation. Mammals adapted to desert climates have lower metabolic rates in general than similar mammals that live in extreme climates. This reduces the internal heat load as well as the water used for evaporation.

Revision questions

1. Explain the concept of regulation (homeostasis).
2. With a specific example of a homeostatic mechanism, draw a diagrammatic representation showing how a body can balance its contents through negative feedback mechanism.
3. How do endotherms keep their body temperatures constant?
4. Outline various ways by which mammals are adapted to arid and semi- arid conditions.
5. Briefly describe the ornithine cycle.
6. Briefly describe how the mammalian renal tubule is adapted to its functions.
7. Explain the causes, effects and prevention of the following disorders in human:
   a) Kidney failure
   b) Kidney stones
   c) Diabetes insipidus
8. Explain the mechanism of osmoregulation in marine elasmobranches.
9. Describe the counter current multiplier system in the mammalian loop of Henle.
10. Describe the mechanism of osmoregulation in mammals.
11. Explain the mechanism of hormonal control of osmoregulation in mammals.

Glossary

Acoelomate An animal that does not possess a body cavity

Adenosine Triphosphate (ATP) is a complex organic chemical that provides energy to drive many processes in living cells

Akaryotes/Acaryotes A cell without nucleus like viruses. Red blood cells are also classified as akaryotes because they lack nucleus after they have developed

Alternation of generation Type of life cycle found in terrestrial plants and some algae in which subsequent generations of individuals alternate between haploid and diploid organisms or refers to the occurrence in the plant life cycle of both a multicellular diploid organism and a multicellular haploid organism, each giving rise to the other.

Ammonotelic organisms Describes an animal that excretes ammonia as the primary waste material. Examples of ammonotelic organisms include protozoans, crustaceans, platyhelminths, cnidarians, fishes, and tadpoles of amphibians.

Anaesthetize Administering a chemical or drug to an animal so as to make an animal unconscious for operation or dissection purposes

Antheridia Male sex organ of algae, fungi, bryophytes, and spore-bearing vascular plants, such as ferns, which produces antherozoids

Archegonia The egg-producing organ occurring in bryophytes (such as mosses and liverworts), ferns, and most gymnosperms. The archegonium is a multicellular, often flask-shaped structure that contains a single egg.

Bacteriochlorophyll Modified chlorophyll that serves as the primary light-trapping pigment in purple and green sulphur bacteria

Bisexual flower A flower with both male and female reproductive structures

Bronchus Passage of airway in the respiratory system that conducts air into the lungs

Browsing A type of herbivory in which an animal feeds on leaves, soft shoots or fruits; generally woody plants such as

shrubs. Such animals are known as browsers. Examples include; giraffe and goat.

Bundle sheath cells — A layer of cells in plant leaves and stems that forms a sheath surrounding the vascular bundle. In C_4 plants it contains chloroplasts and are the site for Calvin cycles.

Caecilians — Group of limbless tropical amphibians that look like large worms or silk snakes. It becomes difficult to differentiate between the head and the tail.

Carboxylation — Chemical reaction in which a carboxylic acid group is produced by treating a substrate with carbondioxide

Carotenoid — Plant pigment responsible for bright red, yellow and orange hues in many fruits and vegetables. They also help chlorophyll from the photo damage during photosynthesis.

Cladistic /Phylogenetics — An approach to biological classfication in which organisms are categorised in groups based on the most recent common ancestry shared traits

Coenzyme Q — A crucial component of the oxidative phosphorylation process in mitochondria which converts the energy in carbohydrates and fatty acids into ATP to drive cellular machinery

Cytochromes — These are electron carrier agents and essential component of the electron transport chain. They can undergo reduction and oxidation (losing or gaining electron) but does not react with oxygen.

Dendrites — Branched protoplasmic extensions of a nerve cell that propagate the electrochemical stimulation received from other neural cells to the cell body

Dissection — The process of cutting open the body part of anaesthetised or deceased animal or plant to investigate its anatomical structure and body systems

Ectotherm — An organism whose regulation of body temperature depends on external sources, such as sunlight or a heated rock surface

Endemic — A native species of animal or plant which are only found

in a restricted area and not other places or an area in which a particular disease is regularly found, or a regular condition or disease found among particular people.

Endotherm Organisms that use internally generated heat to maintain body temperature. Their body temperature tends to stay steady regardless of the environmental temperatures. The endotherms primarily include birds and mammals.

Epiglottis Elastic cartilage covered with a mucosa membrane, found in the throat that prevent the food from entering the windpipe (trachea) and the lungs

Facultative parasites Organisms that can live either as parasites when the host is available or as a free living organism when the host is not available

Foetus Developing offspring inside the maternal uterus (womb) in a prenatal stage between embryonic stage and birth

Fossorial Animals that live underground, digging tunnels and burrows. Some of them are completely subterranean, while others come up to the surface for some hours of the day.

Glycogenolysis A process whereby glycogen which is the primary carbohydrate stored in the liver and muscle cells of animals, is broken down to glucose in order to provide immediate energy and maintain blood glucose levels during fasting. This process occurs primarily in the liver and is stimulated by two hormones, glucagon and epinephrine (adrenaline).

Grazing A type of herbivory in which an animal eats grass or forbs. Such animals are called grazers, and include cows and sheep

Guard cells Specialized epidermal cells of the leaves and stems. They contain chloroplasts used in photosynthesis. They occur in pairs that form a pore between them called stomata, that regulate the gaseous exchange by opening and closing of the stomatal pore.

Haemoglobin (hemoglobin) An iron containing protein molecule of the red blood cell used to transport oxygen in the blood of almost all

vertebrates as well as the tissues of some invertebrates. It is abbreviated as Hb or Hgb.

Hepatopancreatic sphincter Muscular valve which regulates the flow of bile and pancreatic juices

Hibernation Adaptation that helps many animals conserve energy by remaining inactive, greatly slowing their metabolism and reducing their body temperature for days, weeks, or months. Animals hibernate in order to survive long periods.

Homoeothermic animals Animals that maintain a stable body temperature by regulating metabolic processes. Examples are birds and mammals.

Hyperthermia Elevated body temperature due to failed thermoregulation that occurs when a body produces or absorbs more heat than it dissipates.

Hypertonic A condition where the external environment has higher concentration of solutes than the internal environment

Hypotonic A condition where the external environment has lower concentrations of solutes than that of the internal environment

In situ Item being in its natural, normal, or original place or position

Intercostal muscles Several groups of muscles which make and move the chest wall. They run between one rib and another, and they are involved in the mechanical aspect of breathing.

Lean muscle mass Lean mass is the total weight of the body minus all the weight due to your fat mass
Lean mass = total weight – fat mass

Mesophyll cells Photosynthetic cells in plant leaves which are loosely packed and lie between the bundle sheath cells and the leaf surface

Metameric segmentation A series of alike segments running along the length of the body

Nissl's bodies Granular bodies of variable size found in nerve cell bodies and dendrites

Phosphorylation — The process of adding a phosphate group to a molecule or an organic compound

Photoheterotrophs — Organisms that depend on light for energy and complex organic matter for carbon to synthesise their organic requirements

Photolysis — A chemical process by which water molecules are broken down into smaller units through absorption of light during photosynthesis

Photorespiration — A metabolic pathway that occurs in plants in the presence of light; in which ribulose biphoshate carboxylase oxygenase (RuBisCo) fix oxygen instead of carbondioxide to form phosphoglyceric acid and 2-phosphoglycolate; a product which cannot be used in the Calvin cycle.

Phycobilins — Light capturing bilins which are water soluble and contain chromophore that make them coloured, mainly orange, red, and blue pigments found in red algae and cyanobacteria.

Phycoerythrobilin — The red phycobilin, found in some organisms such as cyanobacteria and the chloroplast of red algae which act as the terminal acceptor of energy

Phytopathogenic — Organisms which are pathogenic to plants

Pili — Hair like filaments (tiny hollow projections) that extend from the cell membrane into the external environment. Bacteria possessing pili include *Neisseria gonorrhoeae* and some strains of *Escherichia coli*, and *Salmonella*.

Plasmalemma — Membrane which separates the interior parts of the cell from the outside environment (the extracellular space) that protects the cell from its environment, usually consisting of a lipid bilayer with embedded protein.

Pleural membrane — Thin, slippery and moist membrane surrounding the lungs, it has two layers; the outer layer called parietal pleura and inner layer visceral pleura with a space between them called pleural cavity filled with pleural fluid secreted by the membrane.

Poikilothermic animals Animals whose body temperature fluctuates with that of the environment. Examples include amphibians and reptiles.

Pseudocoelomates Animals with a primitive (false) cavity (pseudocoelum)

Repugnatorial fluid Defensive secretions (odorous fluid) produced by animals, such as certain insects for defence against predators

Ribulose biphosphate (RuBP) An organic substance (a 5 carbon compound) involved in Calvin cycle which is part of the light independent reactions of photosynthesis

Schwan cells Cells in the peripheral nervous system that form the myelin sheath around a neuron's axon. Schwan cells is also called neurilemmocytes.

Svedberg value (s or sv) A measure of a particle's size based on its sedimentation rate, i.e. how fast a particle of given size and shape 'settles' to the bottom of a solution. The units of a ribosome are often described by their Svedberg (s) values, which are based upon their rate of sedimentation in a centrifuge.

Tegument The outer covering of platyhelminths, made up by an epidermal layer and sometimes provided with cilia, spines and glandular tissue

Uniramia A group of arthropods characterised by having appendages (antennae and legs) with only a single ramus (branch). They also have a single pair of antennae and an exoskeleton that is strengthened by tanning process and made water proof by a wax layer. The group has three main classes: the Chilopoda (centipedes), Diplopoda (millipedes) and Hexapoda or Insecta (insects and their relatives).

Ureotelic organisms Animals that excrete urea as the primary nitrogenous waste material. Examples include cartilagenous fish, adult amphibians, and mammals including humans.

Uricotelic organisms Organisms that excrete uric acid, example birds and reptiles

Vaccine A biological preparartion that provides active acquired immunity against a particular disease

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